

Universidad de Concepción

Facultad de Ciencias Ambientales

INTEGRIDAD ECOLÓGICA HISTÓRICA EN EL SISTEMA COSTERO – CORDILLERA DE NAHUELBUTA (CHILE)

Tesis para optar al grado de

Doctora en Ciencias Ambientales con mención en Sistemas Acuáticos Continentales

María Daniela Pedreros Guarda

Profesor Guía: Dr. Rodrigo Abarca del Río

Departamento de Geofísica, Facultad de Ciencias Físicas y Matemáticas

Universidad de Concepción

Profesor Co-Guía: Dr. Robinson Torres

Departamento de Sociología, Facultad de Ciencias Sociales

Universidad de Concepción

CONCEPCIÓN, CHILE

2026

© 2026 María Pedreros Guarda. Se autoriza la reproducción total o parcial, con fines académicos, por cualquier medio o procedimiento, incluyendo la cita bibliográfica del documento.

Comisión Evaluadora de Tesis de Grado

_____

Dr. Rodrigo Abarca del Río
Director de Tesis
Departamento de Geofísica
Facultad de Ciencias Físicas y Matemáticas
Universidad de Concepción

_____

Dr. Robinson Torres
Co-Director de tesis
Departamento de Sociología
Facultad de Ciencias Sociales
Universidad de Concepción

_____

Dr. Roberto Urrutia
Evaluador interno
Facultad de Ciencias Ambientales
Universidad de Concepción

_____

Dr. Francisco de la Barrera
Evaluador interno
Facultad de Arquitectura, Urbanismo y Geografía
Universidad de Concepción

_____

Dr. Jean-François Cretaux
Evaluador interno
Deputy Director
Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
Centre National d'Etudes Spatiales

_____

Dr. Fernando Jaramillo
Evaluador externo
Departamento de Geografía Física
Stockholm University

La vida toma mucho tiempo en estabilizarse. Los ecosistemas intactos que aún tenemos hoy son el resultado de miles de años de ajuste. En ese estado de equilibrio, el sistema se comporta como una sola unidad, cada parte cumple un rol. Hoy la humanidad es la fuerza dominante en el planeta y ha roto sus vínculos orgánicos con la naturaleza. Esta tesis nace del deseo profundo de reconstruir esos vínculos rotos.

Índice

Comisión Evaluadora de Tesis de Grado iv
Índice vi
Índice de figuras ix
Índice de tablas xi
Glosario de siglas y abreviaturas xiii
Resumen xvi
Capítulo I. Presentación 1
1. Introducción 1
1.1. Planteamiento del problema 1
1.2. Marco teórico transversal: la integridad ecológica 9
1.3. Área de estudio y relevancia local de la tesis 15
1.4. Tesis doctoral 21
2. Hipótesis 27
3. Objetivos 28
3.1. Objetivo general 28
3.2. Objetivos específicos (OE) 28
Capítulo II. Natural/cultural landscape integrity in the Nahuelbuta Mountain Range, Chile 30
Abstract 30
1. Introduction 31
2. Study Area 38
3. Methodology 40
3.1. Data 41
3.2. Methods 45
4. Results 47
4.1. Reference and Current States 47
4.2. Anthropogenic Rift 56
5. Discussion 65
6. Conclusion 76
References 79
Capítulo III. A Google Earth Engine application to retrieve long-term surface temperature for medium to small-sized lakes. Case: Nahuelbutan lakes ... 110
Abstract 110
1. Introduction 111
2. Study area 117
3. Data and methods 121
3.1. Data 121
3.2. Methods 124
4. Results 128
4.1. Validation 128
4.2. Spatial and temporal analysis of LSWT 131
5. Discussion 136
6. Conclusions 140
Appendix III.I : Monitoreo ciudadano de calidad del agua para su gestión en sistemas lacustres: Experiencia en Laguna Junquillar 141

Contexto 141
Experiencia de monitoreo ciudadano de calidad del agua en Laguna Junquillar. 144
Datos ciudadanos en la gestión ambiental 147
Referencias 149
Capítulo IV. Thermal patterns in a warm monomictic lake using advanced 3D hydrodynamic modeling 181
Abstract 181
1. Introduction 182
2. Study area 187
3. Data and Methods 192
3.1. Data 192
3.2. Hydrodynamic modelling 199
4. Results 204
4.1. Model validation 204
4.2. Long-term spatial and temporal patterns 212
5. Discussion 216
6. Conclusion 221
Appendix IV.I 224
References 225
Capítulo V. Long-term Lake Water Levels in Central Chile Using Satellite Altimetry and Conceptual Hydrological Modelling Approaches 256
Abstract 256
1. Introduction 257
2. Study area 265
3. Methodology 270
3.1. Work strategy 270
3.2. Data 273
3.3. Water balance construction 284
4. Results 292
4.1. Water balance construction 292
4.2. Water level calibration 299
4.3. Long-term WL reconstruction and climatology 301
4.4. Validation of altimetric against in-situ WL series. 306
5. Discussion 307
5.1. Water level retrieval and forcing 307
5.2. Anthropic forcing in water balance model 311
5.3. Perspectives on this work 313
6. Conclusions 316
Appendix V.I : Monitoreo ciudadano de cantidad del agua para su gestión en sistemas lacustres: Experiencias en los Lagos Nahuelbutanos y humedales de la región del Biobío (Chile). 320
Contexto 320
Proyecto LOCSS 322
Datos ciudadanos en la gestión ambiental 324
References 326
Capítulo VI. Discusiones generales 357
1. Contexto global y local 359
2. Testeo de hipótesis 361

3. Aportes transversales para la gestión ambiental 374
3.1. Integridad natural/cultural 377
3.2. Integridad hidrológica 385
4. Perspectivas de este trabajo 394
Capítulo VII. Conclusiones generales 403
Appendix VII.I : Cobertura/uso de suelo en cuencas de Lagos Nahuelbutanos. 408
Appendix VII.II : Resumen de difusión 409
Referencias 412

Índice de figuras

Figure II.1. Ecological integrity model from Regier (1993a).. 35
Figure II.2. Total, human-caused and natural warming relative to 1850-1900 from 1850 to 2021. 37
Figure II.3. Study area. 39
Figure II.4. Flowchart of the methodology. 41
Figure II.5. Land cover/use: a) Reference map, b) Current map (2015–2024) 49
Figure II.6. Main milestones in the environmental history of the studied territory.....58
Figure II.7. Total population by commune of the study area. 63
Figure III.1. Study area 118
Figure III.2. Flow diagram of the methodology. 128
Figure III.3. Calibrated LSWT (°C) time series (L5, L7, L8, and L9) and in-situ (IS) series in Laguna Grande and in Lake Lanalhue.....129
Figure III.4. Average annual and seasonal climatology of a) Lagoon Grande de San Pedro and b) Lake Lanalhue. 132
Figure III.5. Boxplot of monthly climatology of the LSWT at (a) Lagoon Grande de San Pedro and (b) Lake Lanalhue. Outliers in red.. 133
Figure III.6. Climatology of the monthly average domain of the LSWT in each Nahuelbutan Lake. 135
Figure III.7. Average annual climatology of the Nahuelbutan Lakes based on L8 satellite data. 136
Figure III.8. Kit para Monitoreo de la Calidad del Agua - Alabama Water Quality - LAMOTTE.....146
Figure III.9. Protocolo de monitoreo de calidad del agua en la Laguna Junquillar.....147
Figure IV.1. Study area. 188
Figure IV.2. Time–depth evolution of lake water temperature (LWT) at station FH for 2001–2010.. 206
Figure IV.3. Comparison of LWT time series between in-situ (IS) and COHERENS (COHE) outputs.....207
Figure IV.4. a) Domain average of superficial LWT time series for the period 2013 - 2024. 210
Figure IV.5. Seasonal surface LWT climatologies from COHERENS model and Landsat 8 satellite data. 211
Figure IV.6. Surface and bottom LWT climatologies. 213
Figure IV.7. Monthly anomaly of surface LWT in Lake Lanalhue.....215
Figure V.1. Study area. 267
Figure V.2. Workflow for long-term water level (WL) construction. 271
Figure V.3. Track of S3A over the Lake Lanalhue composite and its visualization in the AlTiS software. 282

Figure V.4. Climatology of the hydroclimatic variables from the datasets used to build the water balance 292
Figure V.5. a) Comparison of in-situ, daily altimetric at one-month time sampling and monthly WB lake levels.. 299
Figure V.6. Climatologies for the period 1950-2022 of water level, air temperature, solar radiation and lake evaporation.....301
Figure V.7. Time series from 1950 to 2022, showing lake water level, precipitation, PDO, inverted AAO and ENSO3.4 indices. Additionally, f) Global Warming index and long-term trend in linear lake evaporation. 303
Figure V.8. Regleta de medición del nivel del agua en Laguna Junquillar..324
Figure VI.1. Batimetría 3D del Lago Lanalhue. 390
Figura VI.2. Area del lago y su derivada con respecto al nivel de agua. 391

Índice de tablas

Tabla I.1: Matriz de trazabilidad metodológica de la tesis doctoral. 25
Tabla VI.1: Modelo de evaluación de integridad ecológica 376
Tabla VII.1: Cobertura y uso del suelo en 2019 para algunas de las Cuencas de los Lagos Nahuelbutanos. 408

Table II.1. Sociodemographic information of the people interviewed. 42
Table II.2. Secondary data used. 43
Table II.3. Geospatial databases. 43
Table II.4. Communal social indicators. 50
Table II.5. Summary of key original ecosystems (circa 1550) and artificial systems (2015-2024) and the metabolism between them and human communities. 54
Table III.1. Main physical, ecological and environmental characteristics of Lakes Laguna Grande de San Pedro and Lanalhue 120
Table III.2. In-situ LSWT sampling stations used and their coordinates in decimal degrees. 122
Table III.3. Satellite data. 123
Table III.4. Mean (μ) and standard deviation (σ) of the LSWT time series from in-situ (IS) and satellite data (L5, 7, 8, and 9). 129
Table III.5. Pairs of series compared (in-situ (IS) and satellite: Landsat 7 (L7), 8 (L8) and 9 (L9)) using the statistical metrics: coefficient of determination, root mean square error, Willmott's index of agreement, and bias. 130
Table IV.1. Main physical, ecological and environmental characteristics of Lake Lanalhue. 191
Table IV.2. Summary of the datasets used to force, initialise and validate the model COHERENS. 192
Table IV.3. Coordinates of LWT and meteorological stations used 196
Table IV.4. Statistical comparison of COHERENS versus in-situ LWT for 2001-2010. 208
Table V.1. Main physical, ecological and environmental characteristics of Lake Lanalhue. 268
Table V.2: Databases available for water level construction. 274
Table V.3. Hydroclimatic databases selected to provide input for the water balance equation for Lake Lanalhue. 279
Table V.4. Comparison of the computation of key variables within the hydroclimatic databases. 280
Table V.5. Mean (μ) and standard deviation (σ) of monthly hydroclimatic databases used to build the water balance. 295

Table V.6. Comparison of available hydroclimatic data using the following statistics: i) square of the correlation coefficient, ii) root mean square error, iii) bias and iv) correlation coefficient.. 296
Table V.7. Precipitation long-term trends, shown as slopes [mm/month]. ..297
Table V.8. Summary of Multivariate Moving-Window Regression Analysis. 306

Glosario de siglas y abreviaturas

3D: Three-dimensional (tres-dimensional).
AAO: Antarctic Oscillation (Oscilación Antártica).
COHERENS: Coupled Hydrodynamical Ecological model for Regional and Shelf seas; modelo hidrodinámico tridimensional avanzado usado para simular la dinámica interna y la temperatura del agua del lago.
CONAF: Corporación Nacional Forestal, Chile.
DGA: Dirección General de Aguas, Chile.
DEM: Digital Elevation Model (Modelo Digital de Elevación).
d (índice de Willmott): Índice de concordancia de Willmott; métrica de ajuste entre modelo y observación que evalúa cuán bien reproduce el modelo los valores medidos.
ECMWF: European Centre for Medium-Range Weather Forecasts; proveedor de los reanálisis ERA5 y ERA5-Land.
ENSO: El Niño–Southern Oscillation (Oscilación del Sur); principal modo de variabilidad climática interanual del Pacífico ecuatorial.
ERA5 / ERA5-L / ERA5-Land: Reanálisis atmosférico y de superficie terrestre del ECMWF. ERA5 es el reanálisis global horario; ERA5-Land (ERA5-L) es la versión de mayor resolución espacial orientada a variables hidroclimáticas de superficie terrestre.
ESA: European Space Agency (Agencia Espacial Europea); proveedora de datos de misiones Sentinel como Sentinel-3A.
FH: Frente Hostería; estación de muestreo in-situ en Lago Lanalhue.
GEE: Google Earth Engine; plataforma de análisis y procesamiento masivo de imágenes satelitales.
GIS: Geographic Information System (Sistema de Información Geográfica).
GLEV: Global Lake Evaporation Volume; base de datos de evaporación lacustre.
L8: Landsat 8; satélite de observación terrestre equipado con el sensor térmico TIRS.
LaSRC: Land Surface Reflectance Code; algoritmo que genera productos de reflectancia superficial (SR) a partir de Landsat.
LL: Lago Lanalhue (abreviatura utilizada en capítulos en inglés).
LSWT: Lake Surface Water Temperature; Temperatura Superficial del Agua de Lago (TSAL). Es en dos dimensiones (2D)
LWT: Lake Water Temperature; temperatura tres-dimensional (3D) del agua del lago, usada para inicializar y validar el modelo COHERENS.

MNDWI: Modified Normalized Difference Water Index; índice espectral usado para extraer cuerpos de agua y limpiar bordes agua-tierra.

NASA: National Aeronautics and Space Administration (Estados Unidos).

NOAA: National Oceanic and Atmospheric Administration (Estados Unidos); organismo que entrega el índice ONI.

NRMSE: Normalized Root Mean Square Error; error cuadrático medio normalizado.

NSCA: Norma Secundaria de Calidad Ambiental (Chile).

ONI: Oceanic Niño Index; índice basado en la temperatura superficial del mar (SST) en la región Niño 3.4, usado para caracterizar eventos El Niño / La Niña.

PB: Playa Blanca; estación de muestreo in-situ en Lago Lanalhue.

PDO: Pacific Decadal Oscillation (Oscilación Decadal del Pacífico); modo de variabilidad climática decadal que modula precipitación y temperatura en Chile central-sur.

PM: Puerto Manzano; estación de muestreo in-situ en Lago Lanalhue.

PP: Puerto Peleco; estación de muestreo in-situ en Lago Lanalhue.

QA: Quality Assurance; bandas de control de calidad en productos satelitales usadas para filtrar píxeles de baja calidad.

R: Coeficiente de correlación de Pearson; mide la fuerza y dirección de la relación lineal entre dos variables.

R^2: Coeficiente de determinación; fracción de la varianza observada explicada por el modelo.

RMSE: Root Mean Square Error; error cuadrático medio entre simulaciones/modelo y observaciones.

S3A: Sentinel-3A; satélite del programa Copernicus utilizado, entre otros usos, para altimetría de cuerpos de agua.

S: Estación Sur (Laguna Grande de San Pedro); punto de monitoreo histórico de parámetros fisicoquímicos.

SC: Sector Centro; estación de muestreo in-situ en Lago Lanalhue.

Sentinel: Programa satelital de la ESA/Copernicus que provee datos ópticos, térmicos y altimétricos.

SST: Sea Surface Temperature; temperatura superficial del mar.

SR: Surface Reflectance; reflectancia superficial corregida de la atmósfera, producto generado por LaSRC.

TIRS: Thermal Infrared Sensor; sensor infrarrojo térmico a bordo de Landsat 8 con el cual se deriva LST.

TSAL: Temperatura Superficial del Agua de Lago; equivalente en español de LSWT.

UTC-4: Coordinated Universal Time – 4 h; zona horaria local de referencia usada en el muestreo in-situ (por ejemplo, mediciones entre 9:00 y 18:00 UTC-4).

WL: Water Level; nivel del agua.

WRF: Weather Research and Forecasting Model; modelo atmosférico regional utilizado como forzante / punto de comparación para ERA5.

Resumen

En el contexto de la crisis ecológica a nivel mundial, se analiza la degradación socio-ecológica del sistema costero-Cordillera de Nahuelbuta con foco en sus Lagos Nahuelbutanos, en el centro-sur de Chile. Como marco teórico transversal se utiliza la integridad ecológica. El objetivo general es *evaluar el cambio de la integridad ecológica del sistema costero - Cordillera de Nahuelbuta entre un estado original (precolombino, 1950, 2000s) y uno actual (2020s) para la restauración socio-ecológica, validando metodologías que puedan ser incorporadas en la gestión ambiental*. Se formulan tres hipótesis formales (H1, H2 y H3) y se explora una emergente (H4). *H1: El sistema ha transitado desde un estado de mayor integridad hacia uno degradado por presiones antrópicas y climáticas*, *H2: lo cual se expresa en la alteración del ciclo del agua y su calidad. H3: La teledetección, modelación numérica y H4: ciencia ciudadana pueden integrarse en el monitoreo ambiental de los sistemas lacustres.*

Se analizan cuatro variables clave: (1) metabolismo socio-ecológico (1550-presente) mediante entrevistas a actores clave y revisión bibliográfica; (2) cobertura y uso del suelo (1550-presente) mediante cartografías (Capítulo II). (3) Temperatura superficial del agua del lago (TSAL), como parámetro de calidad del agua (2000-2024) mediante teledetección con archivos Landsat (Capítulo III) y modelación hidrodinámica avanzada con el modelo COHERENS (2001-2024) (Capítulo IV). (4) Nivel del agua del lago como parámetro de cantidad de agua (1950-2022) mediante modelación hidrológica calibrada con datos altimétricos Sentinel-3A (Capítulo V).

Los resultados revelan la pérdida de integridad en las cuatro variables, lo que prueba H1 y H2. 1) Se transita dede un estado sustentado en el conocimiento tradicional, prácticas sustentables, acceso al agua, alimentos, materiales y medicinas; hacia un estado dominado por usos extractivos

intensivos, con pérdida del conocimiento tradicional y ausencia de control y acceso a los ecosistemas. 2) Hay una drástica reducción del bosque nativo: de un 75% a un 24%, reemplazado por monocultivos forestales (51%), agricultura (23%) y urbanización cerca del núcleo urbano Gran Concepción. 3) En la unidad de estudio Lago Lanalhue (LL), se evidencia una tendencia sostenida al alza en la temperatura del agua (0.12°C/déc en 2000-2024), así como una 4) reducción del nivel del agua de ~5 cm/déc desde 1950.

Para probar H3, se validaron: (i) la teledetección para estimar la TSAL en Laguna Grande de San Pedro y LL, con coeficiente de determinación $R^2 \geq 0.87$, índice de Willmott (d) ≥ 0.97, error cuadrático medio normalizado ($NRMSE$) < 0.12 y $P_{BIAS} \approx 0$. (ii) La modelación hidrodinámica para estimar TSAL en LL, con R^2 = 0.69–0.97, d = 0.88–0.98 y $NRMSE$ = 0.12–0.16 frente a perfiles de temperatura in-situ y (iii) la altimetría para estimar nivel, con $NRMSE$ = 0.0863 y R^2 = 0.8573. Lo anterior muestra la escalabilidad de las herramientas para el monitoreo y gestión de los sistemas lacustres.

El enfoque de restauración socio-ecológica propuesto requiere: i) abordar los conflictos socioambientales mapuche y otros, ii) detener/controlar los forzantes de la degradación, y iii) conservar y restaurar las zonas de valor socio-ecológico.

Capítulo I

Presentación

1. Introducción

1.1. Planteamiento del problema

1.1.1. Contexto

La humanidad se enfrenta actualmente a una crisis ecológica sin precedentes en su historia. Esta crisis ha sido conceptualizada desde diferentes teorías. Los famosos límites planetarios de Richardson et al. (2023) y Rockström et al. (2024), que plantea que ya se han transgredido 6 de los 9 límites biofísicos del planeta, lo que ha comenzado a manifestarse como una crisis ambiental, climática y social de escala global. El concepto de Antropoceno, que ha sido propuesto como una unidad de tiempo geológico que da cuenta de la magnitud de los impactos que la especie humana ha tenido sobre la Tierra, en particular desde la segunda mitad del siglo XX: la "Gran Aceleración", que se manifiesta en el aumento de la temperatura media del planeta, incrementando el dióxido de carbono atmosférico y cambiando el ciclo del carbono a escala planetaria (Lewis & Maslin, 2015). Esta disrupción en el ciclo del carbono es también conocida con el concepto de fractura

antropogénica (Foster, 2022), que se origina por el sistema capitalista global que influencia enormemente las interacciones humanas con el medio ambiente, es decir, el metabolismo socio-ecológico (Clark & York, 2005). Esta teoría revela cómo el capital contribuye a la degradación sistemática de la biosfera (Clark & York, 2005) y es un marco teórico utilizado en el Capítulo II de esta tesis doctoral.

Este problema global ha afectado fuertemente el agua, que es uno de dos elementos que se abordarán en esta tesis, junto con la tierra, desde una mirada de paisaje. El agua es la circulación sanguínea de la biósfera (Falkenmark & Rockström, 2004). Es completamente necesaria para la supervivencia de todas las formas de vida en la Tierra (Jorgensen & Rast, 2007). Desde el punto de vista del agua, la cuenca hidrológica sería la unidad funcional del territorio. El desarrollo global del capitalismo ha fracturado el ciclo natural del agua. Mediante actividades antrópicas desarrolladas en las cuencas que generan residuos que luego son transportados a los cuerpos de agua (Parra et al., 2003), extracción de agua más rápidamente que la capacidad de recarga natural (Wada et al., 2010). Lo anterior ha llevado a una crisis hidrosocial, cuyas características son la escasez de agua, contaminación y falta de acceso a ella (Hargrove, 2021).

Cuando se analice el elemento agua, en esta tesis se pondrá el foco en sistemas lacustres (ej.: lagos, lagunas, reservorios). A nivel mundial, los lagos almacenan 100.000 km³ del agua dulce—90% del agua líquida total de la

superficie terrestre (International Lake Environment Committee, 2007), lo que los diferencia del resto de los sistemas acuáticos. Al actuar como reservorios de agua, regulan la disponibilidad de agua a lo largo del año para personas y ecosistemas, incluso durante los meses secos (Wetzel, 2001). Ecológicamente, los sistemas lacustres cumplen funciones clave como hábitat de biodiversidad acuática y terrestre, zonas de reproducción, alimentación y refugio de especies, incluidas aves migratorias (Wetzel, 2001). Culturalmente, son espacios recreativos que sostienen identidades locales, actividades turísticas y usos tradicionales (Gell et al., 2023). Los lagos permiten amortiguar eventos extremos como sequías prolongadas o lluvias extremas que generan inundaciones, disminuyendo la vulnerabilidad de comunidades humanas y ecosistemas frente a desastres naturales (Gell et al., 2023). Por ello, estudiar su evolución histórica y su estado actual se vuelve estratégico en la gestión territorial.

El cambio climático global y los forzantes antrópicos a escala local han afectados todos los ecosistemas. Los sistemas lénticos (lacustres) han acelerado sustancialmente su proceso de eutrofización (Smith, 2003). La eutrofización representa el proceso de envejecimiento natural, como resultante de la acumulación gradual de nutrientes, un incremento de la productividad biológica y el depósito paulatino de sedimentos provenientes de su cuenca de drenaje. Es decir, los lagos son el reflejo de la sinergia producida por todas las actividades que se desarrollan en la cuenca (Parra et al., 2003).

En condiciones naturales, el proceso de eutrofización en sistemas lacustres es lento y normalmente ocurre a escala temporal de milenios. Sin embargo, por causas antrópicas se ve acelerado a escala temporal de décadas o menos (Parra et al., 2003). Esto altera la dinámica completa del sistema. Cambios en la temperatura afectan los patrones de circulación, estratificación térmica o tiempos de renovación. Aumento en la cantidad de nutrientes y temperatura promueve el crecimiento descontrolado de algas, proceso que se ha vuelto frecuente en los últimos años en sistemas lacustres en todo el mundo (Wurtsbaugh et al., 2019).

Frente a este problema global, desde la década de 1990 ha emergido el llamado “enfoque sistémico”, que reconoce las relaciones intrincadas entre lo ecológico y lo social. Entendiendo que las personas hemos sido la fuerza dominante en esta crisis ecológica, se plantea que también podemos trabajar para revertir o al menos detener el avance de este problema. Desde este enfoque surgen conceptos como el manejo integrado de cuencas (International Lake Environment Committe, 2005), las soluciones basadas en la naturaleza (SbN) (Palomo et al., 2021) o los objetivos de desarrollo sostenible (Naciones Unidas, 2025), promovidos por organismos internacionales como las Naciones Unidas, la Unión Internacional para la Conservación de la Naturaleza o las Conferencias de las Partes.

Estos marcos teóricos promueven la integración de las distintas componentes de la sociedad para el cambio transformativo. Por ejemplo, las

SbN buscan integrar conocimiento, valores y cosmovisiones, con reglas e instrumentos políticos y prácticas de manejo y/o tecnología (Palomo et al., 2021). Estos enfoques buscan detener la degradación de la Naturaleza haciendo cambios en el modelo de desarrollo. En el fondo, estos enfoques buscan recuperar la integridad o un estado deseable de los territorios, para lo cual, la evaluación de estado es fundamental. Evaluar el estado de un sistema sirve para hacerle seguimiento al desarrollo societal y para conocer el punto de partida. Por ejemplo, es posible medir los efectos positivos de determinadas medidas de restauración, o el efecto negativo de determinados forzantes antrópicos.

Esta tesis doctoral tiene un propósito operacional: levantar un sistema de evaluación de estado de un sistema territorial, con foco en el paisaje y en el agua, desde un enfoque eminentemente biofísico, pero incorporando en menor medida la dimensión social en uno de los capítulos, y contextualmente en el resto, como se verá a continuación.

El concepto de “paisaje” admite definiciones y rangos espaciales muy variables en la literatura. Para evitar ambigüedades, cuando se hable de procesos “a escala de paisaje”, se hace referencia al sistema costero - Cordillera de Nahuelbuta o bien a sus cuencas.

. Esta unidad territorial (entre Biobío e Imperial) constituye el marco espacial de integración biofísica y sociohistórica del estudio

1.1.2. Pertinencia y enfoque de investigación

Desde América Latina la crisis ecológica se vive y se interpreta no solo como una disrupción ecológica, sino como la expresión de una historia de colonización, extractivismo y acumulación por desposesión (Clark & York, 2005; Gudynas, 2015). Un primer gran cambio a nivel continental fue la colonización española, lo que provocó cambios en la forma de relacionarse con la naturaleza en América y sentó las bases para cambios estructurales posteriores.

Hoy, aún cuando los colonizadores se han ido formalmente, el legado del colonialismo persiste (Smith, 2016). Desde tiempos de la colonia, el extractivismo ha acompañado la historia latinoamericana. Los extractivismos se diversificaron y se convirtieron en componentes centrales de las estrategias de desarrollo de los gobiernos latinoamericanos desde distintas opciones políticas, y junto a ello se han multiplicado los conflictos socioambientales (Gudynas, 2015). El modelo de desarrollo basado en la exportación de materias primas sin valor agregado ha implicado la transformación de paisajes biodiversos y funcionales en monocultivos extensos (agrícolas y forestales), minería a gran escala y/o infraestructuras de alto impacto.

Si bien el desarrollo dominante en la zona ha sido extractivo, no es el único modelo de desarrollo que existe. El concepto de Buen Vivir, surge como una alternativa de desarrollo, y proviene usualmente de los pueblos

ancestrales (Gudynas, 2017). También existe una sabiduría local cotidiana, de personas dedicadas a la pesca artesanal, recolección, agricultura tradicional. Desde estos sistemas de conocimiento, muchas de las formulaciones modernas de conocimientos presentes en los marcos teóricos globales ya eran conocidas en muchas comunidades locales alrededor del mundo.

Por otro lado, el uso de ideas globales y planetarias corren el riesgo de producir discursos universales (Di Chiro, 2015). En esta línea, se reconoce que el trabajo académico está mediado por estructuras de poder, formas de validación científica, y lógicas de financiamiento que, en ocasiones, replican las mismas dinámicas que se pretenden estudiar (Delgado & Rist, 2016; Smith, 2016). Se reconocen las limitaciones y condicionamientos propios de la producción de conocimiento científico-institucional. Por ello, desde este trabajo, se reconoce el valor del saber local en el proceso de restauración y la necesidad de acceder a él sin caer en el extractivismo. Se escoge un enfoque interdisciplinario para incluir la dimensión social en un trabajo eminentemente físico desde un enfoque opuesto al extractivismo: la reciprocidad (Di Chiro, 2015). Esta dimensión es integrada completamente en un capítulo y contextualmente en los otros, utilizando metodologías de las ciencias sociales como la entrevista, el mapeo participativo, o de las ciencias naturales como la ciencia ciudadana.

Las ciencias sociales ofrecen varias metodologías que permiten incluir el conocimiento local, situando el trabajo en una realidad y contexto local. La más usada es la entrevista. La entrevista es un proceso por el que se dirige una conversación para recoger información (Angrosino, 2012). La entrevista puede ser entendida como el arte de generar ideas a partir de preguntas (Vela, 2019). Lo que busca es hacer que una persona descubra una idea para encontrar la verdad, por medio de preguntas abiertas (Vela, 2019). Ella puede ser una rica fuente de ideas, actitudes y creencias de individuos y la relación con su entorno, así como una descripción más rica de los eventos (Herod, 1993). Las entrevistas aportan con discernimiento acerca de interacciones persona-naturaleza a las que no se puede acceder usando otras técnicas (Kanazawa, 2023).

El mapeo participativo es un enfoque en el que los propios miembros de la comunidad diseñan un proyecto de mapeo para registrar conocimiento local y producir resultados cartográficos (Flavelle, 2003).

Aunque el término ‘ciencia ciudadana’ es relativamente reciente, la participación de personas no especialistas en la observación y generación de conocimiento ha sido inherente a las sociedades humanas. La ciencia ciudadana es la participación del público general en el diseño de la investigación, la recolección de datos y el proceso de interpretación junto con los científicos (Buytaert et al., 2014). Las contribuciones ciudadanas a la ciencia se han implementado con éxito en muchos campos, y los recursos

hídricos son uno de ellos (Assumpção et al., 2018; Buytaert et al., 2014; Morales-Magaña et al., 2020). A través de la ciudadanía es posible recopilar datos y lograr un proceso de toma de decisiones más integrado (Assumpção et al., 2018).

1.2. Marco teórico transversal: la integridad ecológica

Un concepto transversal que está presente en toda la tesis doctoral es la integridad ecológica. Es utilizada como marco teórico para situar la evaluación de estado de un sistema socio-ecológico. Se entiende "estado" como una caracterización en un momento dado y no como un marco para evaluar cambio, el cual se aborda mediante otros enfoques desarrollados en la tesis, por ejemplo, la fractura antropogénica en el Capítulo II y las interpretaciones hidrológicas e hidrodinámicas del Capítulo IV y el Capítulo V.

Existen diversos conceptos para caracterizar la condición de un sistema. Algunos son menos sistémicos y se enfocan en medir parámetros específicos, como los servicios ecosistémicos, el estado, la condición o la salud del ecosistema (Roche & Campagne, 2017), mientras que otros adoptan una perspectiva más integrada al considerar conjuntamente las dinámicas ecológicas y sociales, como en el caso de la integridad ecológica (Regier, 1993a), la sostenibilidad o la resiliencia (Nielsen, 2020).

La integridad ecológica es un concepto biocéntrico (Restrepo & Sal, 2008; Westra & Lemons, 2012), enraizado en la dinámica de sistemas ecológicos combinada con determinados valores humanos (Regier, 1993a). Un ecosistema íntegro mantiene su estructura y funciones ecológicas. Cuando hay presencia humana, un sistema íntegro refleja un uso sustentable por parte de la comunidad humana, la flora y la fauna (Olvera, 2018). Un ecosistema no íntegro, manejado intensivamente, es muy productivo a corto plazo, pero bajo en complejidad, con baja resiliencia frente a desastres naturales y gran dependencia humana para su estabilidad (Zelený et al., 2021).

La necesidad de mantener ciertos niveles de integridad ecológica ha sido ampliamente reconocida a nivel mundial (Roche & Campagne, 2017; Zelený et al., 2021). Debido a su complejidad, la caracterización no puede ser completa, sólo parcial. De todas formas, una caracterización parcial es útil (King, 1993). Una evaluación de integridad ecológica permite conocer el estado de degradación de un espacio geográfico en un tiempo específico, permitiéndonos conocer también las principales causas de los impactos causantes de la degradación (Olvera, 2018).

Operacionalmente, para evaluar el estado o condición de un sistema, se desarrollan un set de indicadores. Existen una amplia cantidad de indicadores ecológicos que hacen referencia a la estructura y funcionalidad de paisaje (ej.: cobertura y uso del suelo (Kwak & Freeman, 2010). Existen otros indicadores hidrológicos que hacen referencia a la funcionalidad hidrológica

(ej.: parámetros físico-químicos, caudal, nivel del agua (Kwak & Freeman, 2010). Existen también indicadores sociales, que dan cuenta de la integridad natural/cultural (ej.: grado de transmisión cultural (W. Xu, 2022). En esta investigación, se trabajará con una caracterización biofísica-social de la integridad, abordándola desde dos focos principales: i) integridad natural/cultural, con variables clave como cobertura y uso del suelo (Kwak & Freeman, 2010) y metabolismo socio-ecológico (Foster et al., 2011). ii) Integridad hidrológica con variables clave como temperatura del agua (calidad del agua) y nivel del agua del lago (cantidad de agua) (Kwak & Freeman, 2010). En cualquier caso, es clave fijar un punto o estado de referencia con respecto al cual los ecosistemas son comparados (Zelený et al., 2021).

Existen antecedentes de evaluación de estado con enfoques holísticos como la integridad ecológica en el mundo. Un ejemplo que aborda la integridad a escala de paisaje, es Open Foris, impulsado por la FAO, que ofrece un conjunto de herramientas de software libre y de código abierto para apoyar a los países en la medición, monitoreo y reporte del estado de sus bosques. Esta iniciativa permite implementar sistemas de medición, reporte y verificación para asegurar la integridad ambiental, dar seguimiento a cadenas de suministro libres de deforestación y monitorear procesos de restauración ecológica, constituyéndose en una referencia internacional para la gestión forestal basada en datos (FAO, 2025).

Un ejemplo que aborda la integridad hidrológica está en Finlandia: el Finnish Institute of Environment, que desarrolló un modelo de análisis de nivel del agua en lagos de Finlandia. Gracias a eso existen alrededor de 30 indicadores de nivel del agua que caracterizan el impacto ecosistémico de la fluctuación del nivel del lago (Y. Gao et al., 2020). Ejemplos de estos indicadores son: nivel del agua mensual, duración de inundación, timing de las crecidas y caídas del nivel del agua a distintas elevaciones (Y. Gao et al., 2020).

Otras aproximaciones a la integridad incluyen la calidad del agua. Un ejemplo es el caso del Freshwater Health Index. Se trata de una iniciativa para evaluar el estado ambiental de diferentes ecosistemas de agua dulce, incluidos los lagos. En este marco teórico, se incluye el estudio de los parámetros de calidad del agua con respecto a umbrales que permiten la biodiversidad acuática (*Freshwater Health Index*, 2025). También existe una iniciativa en Estados Unidos llamada National Aquatic Resource Surveys (US EPA, 2015), conducida por la USEPA (US Environmental Protection Agency) para proveer una evaluación pública de la condición de las aguas de la nación, mediante el estudio de humedales, aguas costeras, lagos y aguas corrientes. La iniciativa que se enfoca en lagos se llama National Lakes Assessment (NLA) (US EPA, 2011).

Un ejemplo que aborda explícitamente la evaluación de integridad ecológica en ambientes con sistemas lacustres proviene de Nueva Zelanda.

Allí, las autoridades se enfocan en la calidad del agua y en la conservación de biodiversidad y hábitats nativos. La integridad ecológica busca unir ambos y extenderlo también hacia la componente cultural (Schallenberg et al., 2018). En ese marco, se desarrolló un conjunto de métricas específicas para aguas continentales, en el marco de la “integridad ecológica de agua dulce”. Esto ha impulsado enfoques más holísticos de monitoreo, gestión y restauración lacustre. En este marco, las evaluaciones bioecológicas LakeSPI se aplican con frecuencia como complemento al monitoreo tradicional de calidad del agua. Sus métricas permiten identificar la distancia respecto a un estado esperado o “prístino”, y constituyen un insumo clave para enfoques multimétricos de evaluación de la integridad ecológica. Hasta la fecha, existen evaluaciones LakeSPI disponibles para más de 260 lagos (National Institute of Water and Atmospheric Research, 2025).

En general, existen pocas iniciativas de este tipo en América Latina, lo que sumado a una brecha estructural de escasez de datos con respecto a países desarrollados, dificulta la gestión ambiental efectiva.

Por ello hoy a nivel global se están validando herramientas complementarias a los datos in-situ para construir estos indicadores: la teledetección, altimetría y modelación numérica (Gholizadeh et al., 2016; Zelený et al., 2021). Una de las grandes ventajas de los métodos de percepción remota es que permiten llevar los indicadores a mapas extendidos en el espacio (Elachi & Van Zyl, 2006) y a resoluciones espaciales de 30

(Landsat) o incluso 10 metros (Sentinel). Además, el cálculo de estos indicadores es automatizable, por lo que se puede convertir en un sistema de monitoreo ambiental (Muñoz Aguayo, 2013). Así mismo, con estas herramientas es posible ampliar el estado del arte de los sistemas lacustres mediante el estudio de aspectos como el cambio histórico de la cobertura del suelo, la distribución espacial de contaminantes (Congalton et al., 2014). Además, con misiones altimétricas es posible conocer las variaciones de superficie, nivel o volumen del cuerpo de agua (Schott et al., 2007), una variable clave para el entendimiento del ciclo hidrológico de la cuenca. Sin embargo, todo esto debe ser validado con datos in-situ (Allan et al., 2016).

Por otro lado, la modelación hidrodinámica permite construir en tres dimensiones (3D) el comportamiento de variables como temperatura, corrientes, estratificación, entre otros, lo que permite entender el funcionamiento físico de un sistema lacustre con mayor profundidad. Al igual que los métodos de teledetección, los modelos deben ser validados con datos in-situ. Una vez hecho esto, es posible extrapolar hacia el pasado y hacia el futuro. La importancia de esto radica en el creciente cambio en los regímenes de mezcla de los sistemas lacustres, que pueden convertir lagos dicmícticos (se mezclan dos veces al año) en monomíctico u oligomíctico (se mezclan menos de dos veces por año), lo que fractura los ecosistemas acuáticos (ESA, 2025b).

1.3. Área de estudio y relevancia local de la tesis

El territorio de estudio corresponde al área comprendida entre los ríos Biobío e Imperial y la Cordillera de Nahuelbuta, que será llamado: *sistema costero - cordillera de Nahuelbuta* (Figure III.1). Un especial foco se pone en los Lagos Nahuelbutanos (Figure III.1), los lagos que se originan por el drenaje de la Cordillera de Nahuelbuta. En este trabajo, se busca caracterizar el estado del sistema parcialmente, considerando dos aspectos. i) La diversidad ecosistémica, y la relación de las personas con los ecosistemas o sistemas antrópicos presentes en el territorio (Capítulo II). ii) Con foco en el agua, se busca caracterizar el estado de los Lagos Nahuelbutanos considerando la calidad y cantidad del agua (Capítulo III, Capítulo IV y Capítulo V). Debido a limitaciones técnicas, la cantidad de agua es cuantificada históricamente para un solo Lago Nahuelbutano: el Lago Lanalhue.

La contribución al conocimiento de esta tesis doctoral es, en primer lugar, conceptualizar la degradación desde un enfoque socio-ecológico a partir del marco de la integridad ecológica. En segundo lugar, avanza de manera explícita el estado del arte tanto en el área de estudio como en la disciplina, a través de aportes específicos en cada capítulo. El Capítulo II conceptualiza la degradación mediante el concepto de integridad ecológica e incorpora, además, una nueva capa de humedales potenciales para 1550, ampliando y refinando el estado de conocimiento existente sobre la cobertura original. El Capítulo III aplica de forma novedosa Google Earth Engine para

estimar la temperatura superficial del agua en lagos incluso pequeños (mayores a 90 m de largo y ancho), lo que extiende el uso de estas metodologías a sistemas que suelen quedar fuera de los análisis globales. El Capítulo V implementa modelación hidrodinámica avanzada en un lago de tamaño medio, utilizando un modelo originalmente desarrollado para el océano, lo que representa una aplicación poco frecuente a nivel internacional y abre una línea metodológica para cuerpos de agua de esta escala. Finalmente, el Capítulo V emplea datos de altimetría satelital como variable de control para calibrar un modelo hidrológico conceptual, sencillo y fácilmente replicable, basado en bases de datos de libre acceso, lo que aporta una vía metodológica accesible para otros sistemas con información limitada.

Chile es un país considerado una “isla biogeográfica”, limitado por el desierto al norte, el océano al oeste y sur, y la cordillera de los Andes al este. Esta zona es uno de los hotspots de biodiversidad más relevantes del planeta (Aguayo et al., 2009; Martínez-Tilleria et al., 2017), con un alto porcentaje de especies endémicas (45%) (Y. Zhao et al., 2016) y una gran diversidad ecosistémica.

La Cordillera de Nahuelbuta, ubicada entre los ríos Biobío e Imperial, es parte de la Cordillera de la Costa y presenta uno de los mayores niveles de biodiversidad y endemismo dentro de ella (Wolodarsky-Franke & Díaz, 2011). Es parte de una región (Ecorregión Valdiviana, desde la región del Maule hasta la región de Aysén) que ha sido identificada como uno de los sitios

prioritarios de conservación a nivel mundial (Wolodarsky-Franke & Díaz, 2011). La Cordillera de Nahuelbuta es una zona de transición climática y ecológica que responde a variaciones locales en la latitud y en la radiación solar (Bravo Orrego, 2018). Actúa como una barrera natural que determina el clima en la zona costera. Las precipitaciones vienen del oeste y al encontrarse con estas montañas quedan parcialmente retenidas a su lado oeste, lo que hace que en la costa (Planicies Litorales) sea más lluvioso que hacia el interior (Depresión Intermedia) (Bravo Orrego, 2018). Por esta razón esta zona costera es abundante en agua, lo que se manifiesta en abundantes ríos, lagos, lagunas y humedales, configuración geográfica que estructuró la organización territorial que los pueblos nativos adoptaron (Huenupil-Marihuen et al., 2010). Los Lagos Nahuelbutanos son un grupo de lagos que comparten una base climática y geológica común (Parra et al., 2003) y que se originan por el desagüe del lado oeste de la Cordillera de Nahuelbuta. Hay más de 30 lagos y lagunas en la zona, distribuidos a lo largo de toda la región de estudio.

Al norte del área de estudio se encuentra el Gran Concepción, un centro urbano e industrial que influye principalmente en las comunas de San Pedro de la Paz, Coronel y Lota. Hacia el sur, las comunas como Arauco, Lebu, Curanilahue, Los Álamos, Cañete, Contulmo, Tirúa y Carahue, son habitadas por comunidades indígenas, poblaciones campesinas mestizas, colonos y agentes comerciales de pequeña, mediana y gran escala, desde finales del siglo XIX (Araya, 2019; Lara et al., 2012).

En las últimas décadas, el territorio ha sido transformado radicalmente, principalmente por la expansión del monocultivo forestal exótico, la agricultura intensiva, la urbanización y la industrialización, bajo políticas públicas neoliberales como el Decreto Ley 701 (Aguayo et al., 2009; Torres et al., 2015). Esta transformación ha implicado una profunda degradación del territorio: reducción del bosque nativo y humedales, homogeneización del paisaje, fragmentación, disminución de la disponibilidad hídrica (Urrutia-Jalabert et al., 2018), y deterioro del aire, el suelo y el agua. Las consecuencias se manifiestan en eventos catastróficos como los megaincendios de 2017 y 2023 (Ortiz et al., 2024), que han afectado principalmente las regiones del Maule, Biobío y Araucanía, coincidiendo con zonas dominadas por monocultivos forestales.

Con respecto a los lagos, en Chile hay 12.784 lagos y lagunas (DGA, 2016). La forma longitudinal que tiene el país permite una diferenciación latitudinal del clima. Esto sumado a las diferencias geológicas permite que de norte a sur se distingan varios grupos o sistemas de lagos, conocidos como “distritos de lagos”. Entre ellos destacan los “Altiplánicos”, “Hipersalinos”, “Nahuelbutanos”, “Araucanos”, “de Chiloé”, “Patagónicos” y “Magallánicos” (Parra et al., 2003). Los sistemas lacustres del área de estudio, Chile y el mundo, se han visto afectados con más frecuencia e intensidad, especialmente en los últimos 8 años, por las floraciones algales. En algunos casos, estas floraciones han provocado la mortandad masiva de organismos

acuáticos (Fundación Terram, 2021), afectando profundamente tanto a los ecosistemas como al bienestar humano.

Frente a la vulnerabilidad de los sistemas acuáticos, el Estado de Chile ha desarrollados instrumentos ambientales de protección, específicamente la normativa hídrica, destacando las Normas de Calidad Ambiental primaria y secundaria) (D.S. N°38 2012). Las Normas Primarias de Calidad Ambiental tienen como objetivo proteger la vida o salud de la población. Mientras que, las Normas Secundarias de Calidad Ambiental (NSCA) apuntan a proteger o conservar el medio ambiente y son diseñadas para un cuerpo de agua determinado (Vera & Rosner, 2020). En las normas secundarias de calidad ambiental para lagos se consideran los siguientes parámetros: conductividad (µS/cm), pH (6,5–8,5), oxígeno disuelto (mg/l y % de saturación), turbidez (NTU), sílice (mg/l), demanda química de oxígeno (DQO) (mg/l), transparencia (m), nitrógeno total (mg/l), fósforo total (mg/l) y clorofila-a (µg/l). Estos parámetros son muestreados por la Dirección General de Aguas (DGA). Además de estos parámetros de calidad del agua, otro parámetro que la DGA muestrea es la temperatura del agua. Si bien este parámetro no está normado en Chile, si está normado en otras partes del mundo, y es un parámetro base de la dinámica del lago (ver Appendix III.I).

Las NSCA buscan caracterizar parcialmente el estado de los cuerpos de agua, con respecto a su calidad, mediante el concepto de estado trófico. Prevenir el cambio de estado trófico (degradación o envejecimiento) de los

sistemas lacustres es fundamental, puesto que con el cambio de estado se pierden funciones ecosistémicas que sostienen la economía y la vida, incluida la humana. Una vez que el cambio de estado ocurre, la restauración es compleja y de alto costo económico y ambiental. Desde esta perspectiva el estado trófico de los lagos es el concepto central de la administración de estos cuerpos de agua, entendiendo que éste describe la relación entre el estado de los nutrientes y la materia orgánica en el lago (Vera & Rosner, 2020).

El problema es que de los 1.251 ríos, y 12.784 sistemas lacustres (Oppliger, 2015), en la actualidad se han implementado las NSCA para cuatro ríos: río Serrano (D.S. N°75, 2010), río Maipo (D.S. N°53, 2014), río Biobío (D.S. N°9, 2015) y río Valdivia (D.S. Nº21, 2024) y sólo dos sistemas lacustres: lago Llanquihue (D.S. N°122, 2010), lago Villarrica (D.S. N°19, 2013) (Vera & Rosner, 2020). Es urgente encontrar la manera de modernizar la gestión ambiental.

El estado de los sistemas lacustres y acuáticos en general, desde el punto de vista de la cantidad de agua en sistemas acuáticos no está normada en Chile, aunque es muy relevante en la gestión integrada del agua en el mundo (ver Appendix V.I). Parámetros comúnmente utilizados para este propósito son el nivel de agua o caudal, monitoreados por la DGA. No obstante, de todos los Lagos Nahuelbutanos, solamente uno (el Lago Lanalhue) tiene monitoreo de nivel del agua. Es muy importante levantar estos parámetros puesto que dan cuenta de procesos como la sequía e

inundaciones, por efectos climáticos o antrópicos, y son un insumo clave para tomar decisiones y hacerles seguimiento a procesos de restauración hidrológica.

Combinando todo lo expuesto, en esta tesis doctoral se parte de la base de que el cambio ambiental ha sido producido vía el cambio en la cobertura y uso del suelo, la que a su vez ha sido modulada por un cambio en el metabolismo socio ecológico. Por lo mismo, monitorear esto es relevante para gestionar el suelo y se realiza en el Capítulo II. La componente social y eco-política es muy importante en este estudio, por lo que es incluida. En la misma línea, entendiendo que la gestión del agua es insumable con parámetros de calidad y cantidad de agua, esta tesis levanta metodologías para monitorear temperatura del agua (calidad del agua) y nivel del agua del lago (cantidad de agua) (Capítulo III al Capítulo V). Si bien la relación de las personas con el agua es extremadamente importante, por limitaciones de tiempo, esta componente ha sido incluida contextualmente en los Capítulos III, IV y V, y expuesta en anexos (Appendix III.I y Appendix V.I) que abordan experiencias de monitoreo ciudadano del agua y que permiten enriquecer el trabajo técnico que en estos capítulos se expone.

1.4. Tesis doctoral

La presente tesis doctoral se sitúa en la coyuntura histórica expuesta y considera la complejidad de las interrelaciones de los sistemas socio-

ecológicos. Desde ahí busca construir un diagnóstico de la integridad ecológica del *sistema costero - Cordillera de Nahuelbuta*, con especial foco en sus sistemas lacustres, en la zona centro-sur de Chile. Este diagnóstico dará cuenta de la degradación ambiental en la zona. Lo hará desde una mirada histórica, construyendo estados de referencia y actuales. Con esta información, propone una mirada restaurativa sobre dicho territorio, que permita recomponer los vínculos entre las personas y la naturaleza desde una perspectiva sistémica.

En este trabajo, se parte de la premisa de que el cambio en el metabolismo socio ecológico, entendido como la forma en que las personas se relacionan con la naturaleza, ha generado una fractura antropogénica que se expresa en alteraciones del ciclo hidrológico y en la calidad del agua. Desde esta mirada, se plantean tres hipótesis (H): *H1: El sistema costero - cordillera de Nahuelbuta ha sido desplazado desde un estado más íntegro hasta uno degradado por efecto del cambio en el metabolismo socio-ecológico a escala local, pero también por efecto del cambio climático. H2: Esta degradación se manifiesta en el cambio del ciclo del agua y en la degradación de su calidad. H3: Las herramientas de teledetección y modelación numéricas pueden integrarse en el monitoreo ambiental.* Estas hipótesis permiten abordar el problema, y además, proponer soluciones. La pregunta de investigación es: *¿Cómo ha cambiado la integridad ecológica en el sistema costero-cordillera de Nahuelbuta entre los períodos precolombino/1950/2000s*

y el presente y cómo se puede evaluar utilizando herramientas costo-efectivas? El objetivo general es: *Evaluar el cambio de la integridad ecológica del sistema costero - cordillera de Nahuelbuta entre un estado original (precolombino, 1950) y uno actual (2015-2024) para la restauración socio-ecológica, validando metodologías que puedan ser incorporadas en la gestión ambiental***.** Así, la intrincada relación entre las personas y la naturaleza se aborda desde un enfoque socio-ecológico.

La integridad ecológica es operacionalizada mediante cuatro variables clave: i) el metabolismo socio-ecológico, ii) la cobertura y uso del suelo, iii) la calidad del agua de los sistemas lacustres mediante la temperatura del agua y iv) la cantidad de agua en ellos mediante el nivel de agua del lago. La metodología utilizada en esta tesis se estructura desde un enfoque sistémico e interdisciplinario acorde al marco de integridad ecológica escogido, combinando herramientas espaciales, satelitales, modelos hidrológico e hidrodinámico, entrevistas cualitativas con actores locales clave, y revisión bibliográfica. Esta articulación permite generar esta investigación, que sienta las bases para un sistema de evaluación de integridad ecológica de los territorios con enfoque de cuencas y que se alinea con una estrategia de monitoreo ambiental pertinente con las realidades locales. El sistema propuesto en base a toda esta investigación es presentado en las Discusiones Generales (Capítulo VI).

Las primeras dos variables (i y ii) son abordadas en el Capítulo II, para lograr el objetivo específico (OE) 1 y tributa principalmente a probar H1, exceptuando lo concerniente al cambio climático. Este capítulo es interdisciplinario e integra herramientas de las ciencias naturales y sociales para abordar la degradación ambiental en todo el sistema costero – Cordillera de Nahuelbuta. Las siguientes variables (iii y iv) son abordadas en los Capítulos III, IV y V, asociados a los OE 2, 3 y 4, respectivamente, que tributan a probar H2 y H3 en su totalidad, y tributan a probar H1 en lo respecta al cambio climático. Estos capítulos se enfocan en obtener estos parámetros de calidad y cantidad de agua en los sistemas lacustres del territorio de estudio (Lagos Nahuelbutanos) con herramientas de teledetección y modelación numérica, desde una perspectiva eminentemente biofísica. Debido a la escasez de datos, se analizarán más profundamente casos específicos en representación de la dinámica hidrológica y climática local. Los sistemas lacustres con mayor observación, disponibilidad de datos y estudios previos son la Laguna Grande de San Pedro y el Lago Lanalhue, razón por la cual se validarán las metodologías de percepción remota y modelación hidrológica e hidrodinámica en estos sistemas lacustres.

En los Capítulos III, IV y V, la dimensión social se incorpora únicamente de manera contextual, dado que la validación técnica de las metodologías desarrolladas en dichos capítulos al momento de publicar exige un alto nivel de rigurosidad. En el marco temporal de una tesis doctoral de tres años no

resulta posible, además, integrar en profundidad la dimensión social, por lo que esta se aborda como experiencias de ciencia ciudadana presentadas en los anexos: Appendix III.I y Appendix V.I, que corresponden a extensiones transdisciplinarias de la tesis doctoral. En estos anexos, se presentan dos proyectos de monitoreo ciudadano participativo. Los trabajos dieron origen a sistemas de monitoreo ciudadano de calidad y cantidad del agua en varios lagos Nahuelbutanos y humedales del Gran Concepción, además de una guía o protocolo para su uso. Las técnicas utilizadas fueron mapeo participativo y focus group.

En la Tabla I.1, se resume la metodología mediante una matriz de trazabilidad metodológica, lo que facilitará la lectura de la tesis doctoral. Para ello, se relacionan los objetivos con las hipótesis, se explicitan las variables clave, los métodos principales, las fuentes de datos principales y los capítulos asociados, los cuales desarrollan en detalle en cada objetivo específico.

Tabla I.1: Matriz de trazabilidad metodológica de la tesis doctoral.

OE	H	Marco teórico	Variables clave	Método principal	Fuente de datos	Cap.
1	H1	i) Integridad ecológica (natural/cultural), ii) Fractura antropogénica.	i) Cobertura y uso del suelo, ii) metabolismo socio-ecológico a escala de paisaje	Entrevistas cualitativas, revisión bibliográfica, análisis geoespacial.	Entrevistas, cartografías CONAF, bibliografía y archivos históricos, DEM	Capítulo II
2	H3	i) Integridad ecológica, ii) monitoreo remoto de aguas continentales, iii) manejo	i) TSAL satelital (como parámetro de calidad del agua), ii)	Análisis geoespacial, teledetección satelital, validación con datos in-situ.	Datos in-situ (DGA), archivos Landsat 7, 8 y 9.	Capítulo III

		integrado de cuencas	estadísticos (R^2, d, RMSE, bias)			
3	H1 H2 H3	i) Integridad ecológica, ii) modelación hidrodinámica de sistemas lacustres	i) Temperatura del agua (TAL) modelado (como parámetro de calidad del agua), ii) estadísticos (R^2, d, RMSE)	Modelación hidrodinámica avanzada 3D (COHERENS), validación con datos in-situ y satelitales.	Datos in-situ (DGA), output de modelo hidrodinámico COHERENS, archivos Landsat 8.	Capítulo IV
4		i) Integridad ecológica (hidrológica), ii) manejo integrado de cuencas, iii) monitoreo participativo del agua	i) Nivel del agua del lago modelado e in-situ, ii) Nivel del agua con datos participativos.	Modelación hidrológica conceptual, calibración con datos altimétricos, validación con datos in-situ, monitoreo ciudadano del agua	Datos in-situ (DGA), output de modelo hidrológico conceptual, S3A.	Capítulo V

La tesis se organiza en siete capítulos. Este es el Capítulo I. En el Capítulo II se reconstruye un estado de referencia precolonial y un estado actual del territorio mediante dos variables: la cobertura y uso del suelo y el metabolismo socio ecológico. Los métodos incluyen análisis geoespacial y satelital, entrevistas a actores clave y revisión bibliográfica histórica. El Capítulo III y el Capítulo IV sientan las bases de un sistema de monitoreo de calidad del agua a través de un parámetro clave: la temperatura del agua. Se reconstruye históricamente este parámetro mediante teledetección (Capítulo III) y modelación hidrodinámica (Capítulo IV). En el Capítulo V se analiza el ciclo hidrológico histórico desde 1950 para un caso de estudio en particular:

el Lago Lanalhue, para obtener entendimientos que sirven para toda el área de estudio. El Capítulo VI propone una discusión general de la tesis doctoral y una ruta de restauración socio-ecológica orientada a la restauración de la integridad ecológica utilizando la información y metodologías levantadas en este trabajo. Finalmente, en el Capítulo VII se presentan las conclusiones generales de este trabajo doctoral.

2. Hipótesis

En este trabajo, la premisa es que el cambio en el metabolismo socio-ecológico dado por la relación de las personas con la naturaleza en un contexto extractivista, ha producido una fractura antropogénica que se manifiesta en el cambio del ciclo hidrológico y la degradación de la calidad del agua. Para resolverlo, la gestión ambiental debe fortalecerse, y las herramientas de teledetección y modelación numérica que se validan en este trabajo pueden cumplir ese rol. En este contexto, se plantean tres hipótesis.

H1: El sistema costero - Cordillera de Nahuelbuta ha sido modificado desde un estado más íntegro hasta uno degradado por efecto del cambio en el metabolismo socio-ecológico a escala local, pero también por efecto del cambio climático.

H2: La degradación del sistema costero – Cordillera de Nahuelbuta se manifiesta en el cambio del ciclo del agua y en la degradación de su calidad en los Lagos Nahuelbutanos.

H3: Las herramientas de teledetección y modelación numérica pueden integrarse en el monitoreo ambiental para una gestión efectiva de los Lagos Nahuelbutanos.

3. Objetivos

3.1. Objetivo general

Evaluar el cambio de la integridad ecológica del sistema costero - Cordillera de Nahuelbuta entre un estado original (precolombino, 1950, 2000s) y uno actual (2020s) para la restauración socio-ecológica, validando metodologías que puedan ser incorporadas en la gestión ambiental.

3.2. Objetivos específicos (OE)

Para evaluar el cambio de la integridad ecológica, se va a operacionalizar a través de cuatro variables clave: i) metabolismo socio ecológico, ii) cobertura/uso del suelo (OE 1, Capítulo II), iii) temperatura del agua superficial (OE 2, Capítulo III) y 3-dimensional (3D) (OE 3, Capítulo IV) y iv) nivel del agua del lago (OE 4, Capítulo V). Además, para validar

metodologías que puedan ser incorporadas en la gestión ambiental, se validan métodos de teledetección, modelación hidrológica e hidrodinámica y altimetría. Los objetivos específicos responden a este fin y se presentan a continuación.

1. Construir un modelo conceptual de integridad natural/cultural a escala de paisaje original (precolombino) y actual (2020s) y analizar los mecanismos de cambio en el *sistema costero - Cordillera de Nahuelbuta* (Capítulo II).

2. Analizar espacial y estacionalmente la temperatura superficial del agua de los Lagos Nahuelbutanos en el período 1999-2024, como indicador de integridad hidrológica, validando métodos de teledetección (Capítulo III).

3. Analizar la temperatura del agua del Lago Lanalhue, como indicador de integridad hidrológica en el período 2000-2025, validando métodos de modelación hidrodinámica avanzada (Capítulo IV).

4. Analizar el nivel del agua del Lago Lanalhue, como indicador de integridad hidrológica, en el período 1950-2022, validando métodos de modelación hidrológica conceptual y altimetría (Capítulo V).

Capítulo II

Natural/cultural landscape integrity in the Nahuelbuta Mountain Range, Chile

Abstract

Restoration is essential to address degradation and require assessing the ecosystems' state. Around Nahuelbuta mountain range, the objective is to construct a conceptual model of the difference between the reference state of the landscape (pre-Columbian, 1550) and its current condition, and to discuss the mechanisms of change (dispossession, land occupation, neoliberal policies). A hybrid methodology was employed, combining interviews, literature review, and geospatial data, focusing on two variables: land cover/use and socio-ecological metabolism. Results reveal a drastic reduction of native forest: from 7,661.4 km² (75% of the territory) to 2,553.8 km² (24%). In the lowlands, grasslands and shrublands (2,516 km², 24%) intermingled with wetlands, supported settlements and now occupy just 1,153.2 km² (11%). Simultaneously, exotic forestry plantations expanded to 5,209.8 km² (51%), agriculture to 2,411 km² (23%), and urbanization around Concepción keeps growing. In the reference state, communities practiced low-input, seasonally synchronized management grounded in traditional knowledge, with broad

access to and control over forests, wetlands, and waters that supplied food, medicine, materials, and drinking water directly from ecosystems. Today, this metabolism is dominated by extractive, intensive uses (notably forestry), territorial privatization, and fragmentation that both restrict access and marginalize traditional knowledge. Therefore, our integrity model classifies the system in low integrity.state, in which degradation is a result of the disruption of the functional human-ecosystem relationship. We advocate for socio-ecological restoration, which demands: (i) tackle the Mapuche and other socio-environmental conflicts, (ii) stopping degradation drivers, and (iii) preserving and restoring biocultural landscapes.

1. Introduction

Human-induced landscape degradation is one of the most pressing global challenges (B. Clark & York, 2008; Lewis & Maslin, 2015). In response, ecological restoration emerges as a necessary process. However, there are significant knowledge gaps that hinder restoration efforts: What should be restored? What was originally there? What constitutes an "original" state? These questions require a deep and historically informed analysis of degradation in order to clearly determine when the problem began and what possibilities exist for reconstructing conditions prior to its onset. Comparing the original state with the current one is essential for identifying priority areas for restoration (L. Huang et al., 2022).

In this context, the study explores the deep, human-induced socio-environmental degradation around Nahuelbuta Mountain Range, a historical biodiversity refuge (Wolodarsky-Franke & Díaz, 2011) and a region of global biodiversity significance (Aguayo et al., 2009). Located in south-central Chile—one of the country's most populated and industrialized regions—this area reflects how political dimensions play a crucial role in degradation processes, particularly through the promotion of anthropogenic drivers such as exotic monoculture forestry, industrialization, intensive agriculture, and rapid urbanization (Aguayo Arias, 2008; Echeverría et al., 2014; Torres et al., 2015). The article addresses the question: How has the ecological integrity of the coastal system - Nahuelbuta Mountain Range landscape changed from 1550 to the present, and what mechanisms have driven this change? We hypothesize that the system has shifted from a state of higher to lower ecological integrity due to political processes, especially during the 19th century. This transformation has profoundly altered both the natural landscape and the socio-ecological metabolism.

In this context, assessing ecosystem conditions is fundamental (Vlasova et al., 2021). One of the key physical variables for evaluating ecosystem state at the landscape scale is land cover and land use (Kwak & Freeman, 2010; Torres et al., 2015), which has led to the development of several methodological approaches for its analysis (Brown et al., 2022; Vergara Díaz et al., 2018; Y. Zhao et al., 2016). While many studies

acknowledge the importance of the territorial component (Aguayo Arias, 2008; Winkler et al., 2021), the problem runs deeper. Changes in land cover and use—ecological phenomena—are often driven by public policies enacted within power asymmetries (Budds, 2013; Tedesco et al., 2023), and through processes of cultural erasure (Ortiz et al., 2024) that reshape the socio-ecological metabolism (Foster, 2022). This complexity necessitates a systemic understanding of the landscape as a socio-ecological system (Fischer et al., 2021) and calls for a holistic approach that integrates interdisciplinary academic knowledge with Indigenous, traditional, and local perspectives (Vlasova et al., 2021). However, such integration remains rare in practice (Martínez-Fernández et al., 2021).

Various concepts exist to characterize the condition of a system. Some are less systemic and focus on measuring specific parameters, such as ecosystem services, ecosystem state, condition, or health (Roche & Campagne, 2017), while others adopt a more integrated perspective by considering ecological and social dynamics together, as in the case of ecological integrity (Regier, 1993a), sustainability, or resilience (Nielsen, 2020). Ecological integrity is a biocentric concept (Restrepo & Sal, 2008; Westra & Lemons, 2012), rooted in the dynamics of ecological systems combined with specific human values (Regier, 1993a). From a systems dynamics perspective, species—and thus the ecosystems they form—are autopoietic, meaning they possess mechanisms through which they self-

replicate, maintaining successful functions and favoring adaptations that improve performance (Kay & Schneider, 1995). Ecosystems are also resilient, allowing them to maintain functionality in the face of “normal” disturbances, that is, stressors with a long history of recurrence that the system has internalized over time, leading to the development of adaptive mechanisms that sustain systemic functioning (Holling, 1986). Within such normal ranges, systems may return to their pre-disturbance state. If disturbances exceed these thresholds or tipping points, however, systems shift to new states. Human interventions impose stressors that differ in type and magnitude from natural ones (Regier, 1993a), forcing the systems into new, unnatural states characterized by low ecological integrity—disintegrated (Holling, 1986) or degraded (Zelený et al., 2021). While no characterization of a system can be complete, even partial assessments can be highly informative (Regier, 1993a). In this article, we focus specifically on cultural/natural integrity, at a landscape level, which is explained graphically in Figure II.1.

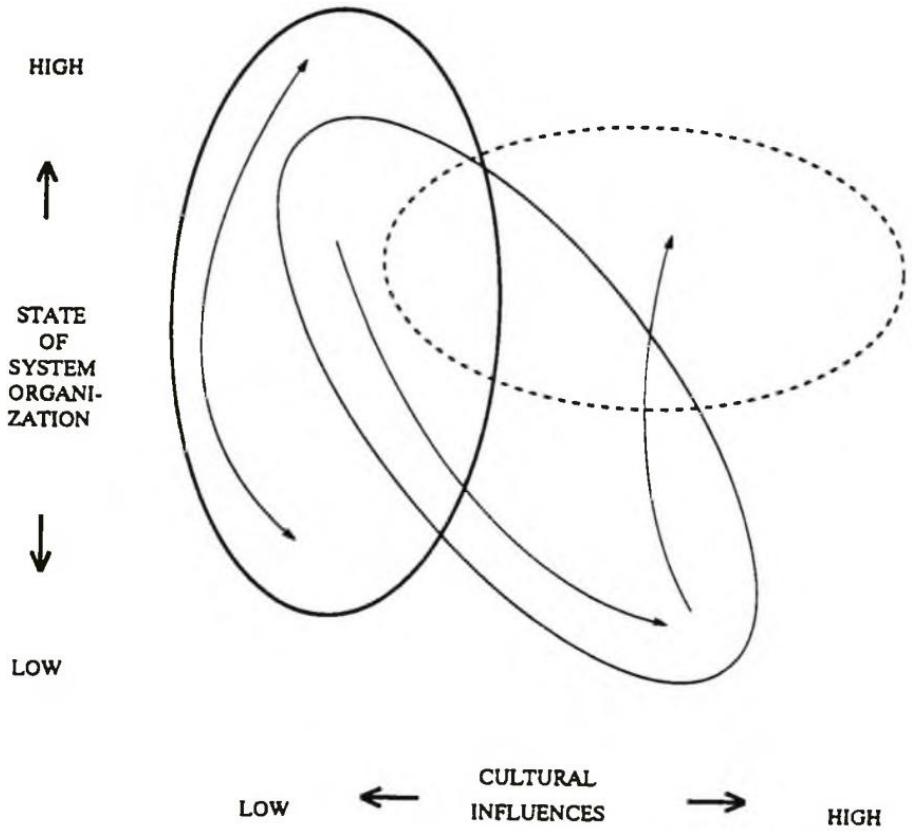


Figure II.1. Ecological integrity model from Regier (1993a).The vertical ovoid reflects a natural or pristine state without human presence. The diagonal ovoid in the center reflects different levels of ecosystem degradation due to cultural abuse. The horizontal ovoid reflects a healthy natural/cultural ecosystem or landscape mosaic. Model and figure taken from Regier (1993a).

Numerous authors have noted that cumulative human-driven ecological alterations are transforming the functional metabolism of the planet as a whole, beyond the local scale. This is conceptualized through the key concept of the anthropogenic rift (Foster, 2022): the rupture in Earth's metabolism or functioning caused by human activity within the framework of capitalist society. Homo sapiens has existed within the biosphere for approximately 250,000

years, co-evolving with it, through connections in terms of social conditions, health, culture, justice, and survival (Folke et al., 2021). This relationship constitutes the metabolism between people and nature or socio-ecological metabolism (Foster et al., 2011). However, over the past 70 years, this metabolism has undergone significant changes, altering the usual cycles of ecosystems (Clark & York, 2005). In short, the transformation of socio-ecological metabolism has fundamentally changed both ecosystems and the state of the planet (B. Clark & York, 2008). These transformations have been well documented by Steffen et al. (2015) and Rockström et al. (2024). Given their global scale, these changes have prompted debates about the beginning of a new geological epoch: the Anthropocene (Folke et al., 2021; Foster, 2022; Lewis & Maslin, 2015), where humanity becomes the primary force impacting the Earth (Foster, 2022), as shown in Figure II.2.

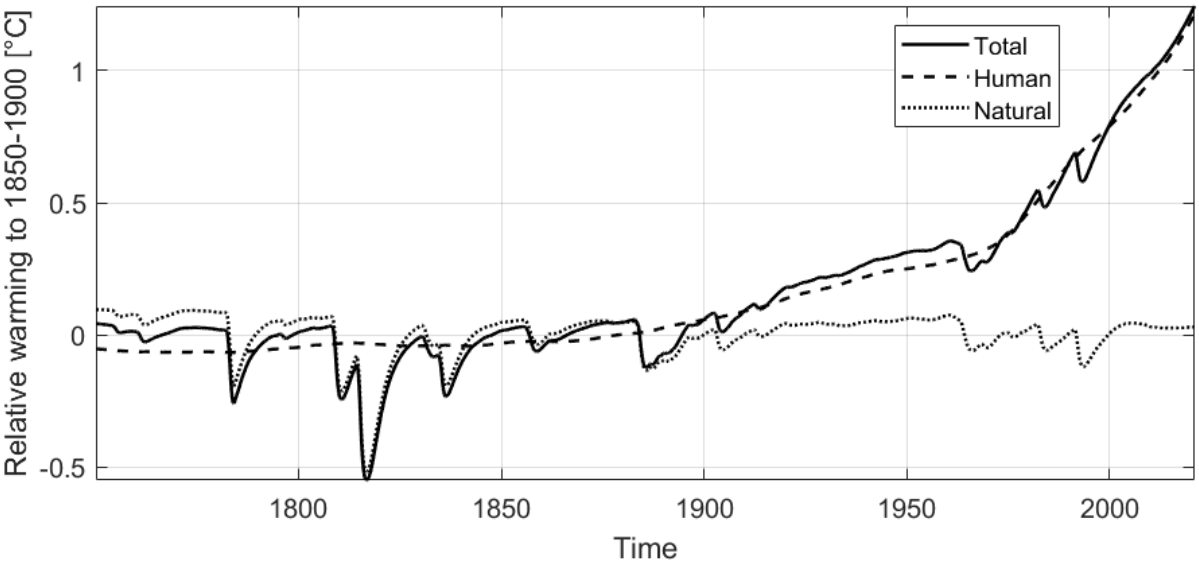


Figure II.2. Total, human-caused and natural warming relative to 1850-1900 from 1850 to 2021 (Data available in Haustein et al. (2017)).

This interdisciplinary study offers a novel perspective that dissolves the blurred line between the cultural and the natural. The premise of this article is that territories worldwide have undergone a transformation in state or condition due to a rupture in the metabolism between people and nature—shifting from a state of integrity (high ecological integrity) to one of degradation (low ecological integrity). In this paper, the concept of “anthropogenic rift” refers to the loss of integrity in the Nahuelbuta Mountain Range region, driven by political, social, economic, ecological and cultural forces that have reshaped socio-ecological metabolism. In this study, the concept of ecological integrity is operationalized through two observable dimensions: (i) land cover/use, and (ii) socio-ecological metabolism. Consequently, the objective is to develop a conceptual model that represents two states of ecological integrity: an original pre-Columbian (circa 1550) state of high integrity, and the current state (represented by the most recent available data, see Section 3.1.) of low integrity, as well as the mechanisms of change that led from one to the other, using a hybrid methodology that combines (i) qualitative interviews of stakeholders, (ii) literature review, and (iii) spatial data analysis.

Contextualizing in the present doctoral thesis, this chapter aims to achieve the specific objective 1: Build a conceptual model of the original (pre-Columbian) and current (2015-2024) state and analyze the mechanisms of

change in the coastal system - Nahuelbuta mountain range. It also seeks to prove the hypothesis 1: The coastal system – Nahuelbuta mountain range has been moved from a more intact state to a degraded one due to the effect of changes in socio-ecological metabolism at the local level, but also due to the effect of climate change, by focusing on the anthropic aspect of degradation.

2. Study Area

The study area: the coastal system - Nahuelbuta Mountain Range is located in south-central Chile. The Nahuelbuta Range refers to the section of the Coastal Range situated between the Biobío and Imperial rivers, spanning parts of the Biobío and Araucanía regions (Figure II.3). The Nahuelbuta Range is one of the areas within the Coastal Range with the highest levels of biodiversity and endemism. It is part of the Valdivian Ecoregion, which stretches from Chile's Maule Region in the central zone to the Aysén Region in Patagonia, and has been identified as one of the world's priority sites for conservation (Wolodarsky-Franke & Díaz, 2011). This mountain range acts as a natural barrier that retains precipitation from the west (Bravo Orrego, 2018), resulting in high water availability. This is reflected in the presence of numerous rivers, wetlands, lagoons, and lakes, most of which are located in the Biobío Region, with some in the Araucanía Region.

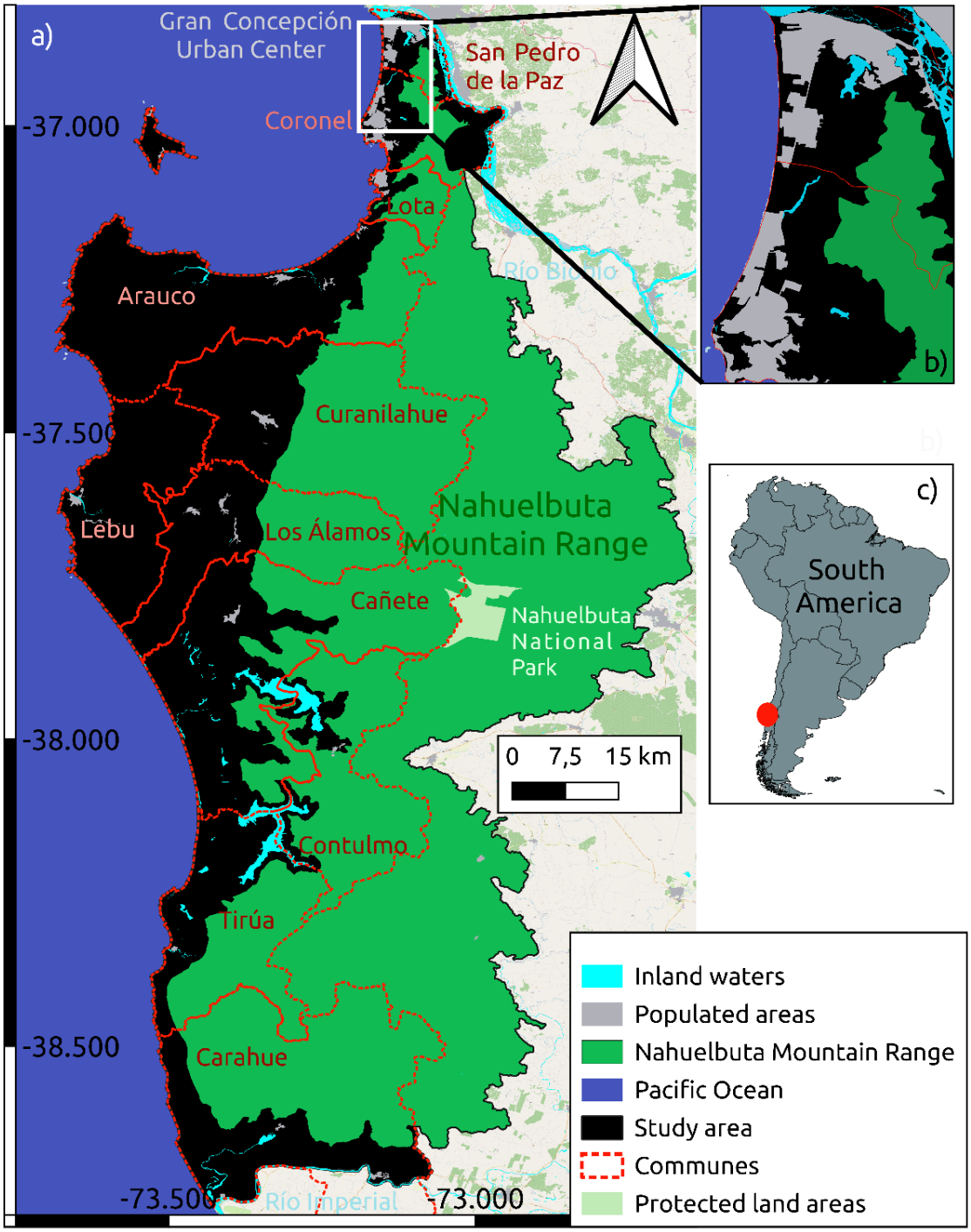


Figure II.3. a) Study area. To the west is the Pacific Ocean; to the east, the Nahuelbuta Range. To the north, the Biobío River and the urban center of Gran Concepción; to

the south, the Imperial River. b) Zoom into the northern zone of the study area. c) Location.

To the north of the study area lies Gran Concepción, an urban and industrial center that mainly influences the municipalities of San Pedro de la Paz, Coronel, and Lota. Toward the south, in municipalities such as Arauco, Lebu, Curanilahue, Los Álamos, Cañete, Contulmo, Tirúa, and Carahue, a diversity of populations coexist—including Indigenous communities, mestizo peasant populations, settlers, and commercial agents of small, medium, and large scale—since the late 19th century (Araya, 2019; Lara et al., 2012).

The study area was delineated by integrating the spatial layers of the selected communes with the Nahuelbuta Mountain Range shapefile, detailed in Table II.3.

3. Methodology

The methodology is summarized in Figure II.4. Two states of the socio-ecological system are defined: a reference or original state (circa 1550) and a current state. The current state is considered to be adequately represented by the selected datasets (Section 3.1.), which constitute the most recent and reliable sources available.

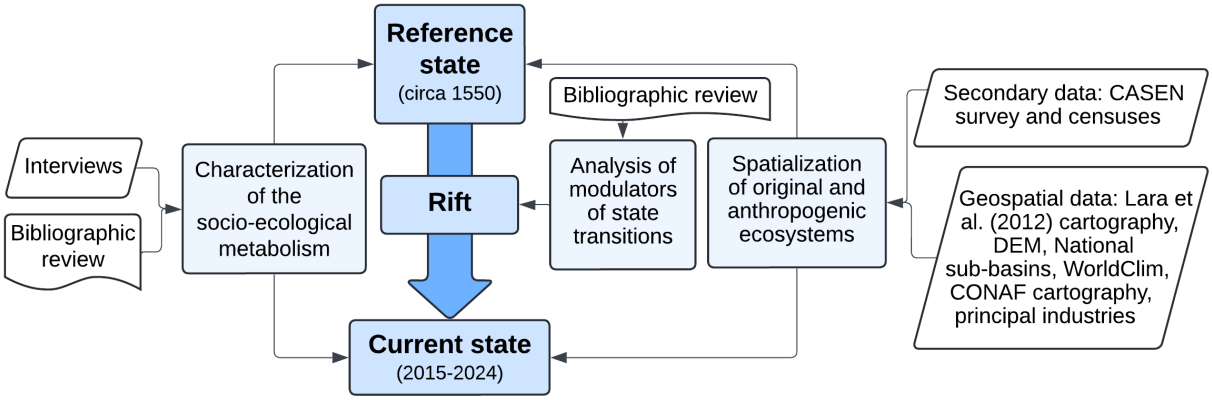


Figure II.4. Flowchart of the methodology. Reference and current states are characterized using two variables: the socio-ecological metabolism and land cover/use. The former is constructed through qualitative interviews and literature review; the latter through geospatial data. Both plus the metabolic rift between both states are analyzed using bibliographic review. Source: Own elaboration

3.1. Data

3.1.1. Interviews

Sampling should be conducted with the saturation level in mind, that is, the point at which narratives become redundant or begin to repeat themselves (Gubrium et al., 2012), a prudent number of interviews to reach saturation is between 6 and 12. In this case, ten unstructured qualitative interviews were conducted between 2021 and 2022 across the study area (Table II.1). The interviews aimed to address two central questions: (i) Which ecosystems are relevant in the territory, where are they spatially located, and what has been people's relationship with these ecosystems (socio-ecological metabolism)? (ii) Through which mechanisms have anthropogenic drivers altered the socio-

ecological metabolism, leading to a degraded territorial state? Interviews were fully transcribed and analyzed using Atlas.ti software, with informed consent.

Table II.1. Sociodemographic information of the people interviewed. The technique used in all cases was the unstructured qualitative interview. Source: Own elaboration.

Interview (year)	Occupation/role	Age (years)	Place
E1 (2021)	Socio-environmental group leader	37	San Pedro de la Paz
E2 (2022)	Scientist	>50	
E3 (2022)	Socio-environmental activist	55	San Pedro de la Paz y Coronel
E4 (2022)	Scientist	60	Coronel
E5 (2022)	Socio-environmental leader	>65	Los Álamos
E6 (2022)	State Project Coordinator	40	Cañete
E7 (2021)	Mapuche inhabitants	>30, >50	Contulmo
E8 (2021)		>70	
E9 (2021)	Traditional farmer	>70	
E10 (2022)	Civil servant and Mapuche inhabitant	40	Tirúa

3.1.2. Secondary sociodemographic data

In order to broaden the analysis, the study was supported by secondary data, which are detailed below and summarized in Table II.2. The 2020

National Socioeconomic Characterization Survey (CASEN) was used. The population censuses conducted in Chile from 1952 to 2017 were also used.

Table II.2. Secondary data used. Source: Own elaboration.

Database	Term	Variables	Source
CASEN Survey	2020	Poverty rate and percentage of indigenous people	BCNa (2023)
Census	1952-2017	Percentage of urban and rural population (2017) and amount of population by commune (1952-2017).	INEa (2017); INEb (2024); BCNb (2017); BCNc (2002)

3.1.3. Geospatial Data

Geospatial databases were used to represent the territorial landscape in both reference and current states (Table II.3).

Table II.3. Geospatial databases.

Data base	Description	Source	Available years (year used)
i) Cartographic reconstruction of land cover around 1550 adapted from Lara et al. (2012).	Land cover classes: native forest, mosaic and grasslands and shrublands.	Lara et al. (2012)	1550
ii) DEM ALOS-PALSAR	Digital elevation model (DEM), with a 12.5m spatial resolution.	JAXA (NASA, 2025)	2006-2011

iii) Sub-basins	Sub-basins at national level in shp format provided by the General Water Directorate (DGA).	Ministerio de obras públicas (IDE, 2025)	2017
iv) WorldClim Climatology V1	Precipitation climatology at 1km spatial resolution, averaged over the period 1950-2000.	University of California, Berkeley (EEDCa, 2024)	1950-2000
v) CONAF 2021 land cover/use mapping	Land cover/use classes (code): urban and industrial (01), agricultural (02), grasslands and shrublands (03), forest plantation (0401), native forest (0402), mixed forest (0403), wetlands (05), areas without vegetation (06), inland waters (08)	CONAF (IDE minagri, 2024)	2001, 2013, 2016, 2017, 2019 y 2021 (2021)
vi) Principal industries	Geographical location of the main industries (longitude, latitude): Coronel Thermoelectric Plants: Bocamina (-73.1672,-37.0228) and Santa Maria (-73.1322,-37.0413) , Coronel Industrial Park (-73.1665,-36.9696), Arauco Horcones Plant (-73.2016,-37.2054) and Modernization and Expansion of Arauco Plant (MAPA): -73.2140,-37.2011.	N/A	
vii) Shape of Nahuelbuta Mountain Range	Shape that delimits the Nahuelbuta Mountain Range	Otavo & Echeverría (2017)	N/A

3.2. Methods

3.2.1. Socio-Ecological Metabolism

For both territorial states (reference and current) and the rift between them, the associated socio-ecological metabolism is described. To operationalize it regarding the natural and artificial (eco)systems in terms of practices, uses, and associated cultural meanings at the landscape scale, the concept of socio-ecological metabolism was qualitatively characterized through functional categories: i) cosmovision, ii) traditional knowledge, iii) land practices, iv) control and access to ecosystems. This analysis was based on qualitative interviews and a literature review and is supported by secondary sociodemographic data (Section 3.1.2.).

3.2.2. Land Cover/Use

With a focus on landscape, the original state (circa 1550) is represented based on the work of Lara et al. (2012), which includes a map delineating the study area in native forest, grasslands, and shrublands. It was digitized and adapted to our study area. Wetlands were added to the model based on their potential distribution.

Regarding uncertainty In reconstructing the circa-1550 baseline, Lara et al. (2012) note that the historical documents used are constrained by their availability and by source subjectivity, period-specific ideals, and selectivity;

the archaeological record is fragmentary and cultural syntheses for ~1550 are scarce and not up to date. Besides, where no records or inferred Indigenous intervention exist, areas currently covered by native forest are assumed to have originally been native forest.

Potential wetlands are areas where there is a high probability that a wetland currently exists or once existed. This was done by replicating the methodology developed by Hu et al. (2017), which uses an indicator that estimates the likelihood of wetland existence at a given site based on watershed morphology and precipitation, called PTWI, which stands for Precipitation Topographic Wetness Index. The formula is shown in Equation 1.

$$PTWI = log\ (P_r / Tan\beta) \qquad (1)$$

, where P_r is the drainage basin area (calculated from national Sub-basins, Table II.1) multiplied by the average annual precipitation (from the WorldClim climatology V1, Table II.3), and $Tan\beta$ is the topographic slope (derived from the 12.5m resolution DEM, Table II.3). The procedure was implemented in the Google Earth Engine (GEE) software.

Uncertainty in the original wetland layer stems from both the index formulation and the input datasets used to compute it (precipitation and the DEM). The index provides a single output, whereas wetlands are highly dynamic throughout the year (Nhamo et al., 2017), therefore, this approach

necessarily simplifies their delineation. In the absence of older precipitation datasets, it is assumed that precipitation conditions around 1550 were comparable to those of the 1950–2000 reference period. Likewise, because no high-quality historical DEM is available, the 2006–2011 DEM is assumed to be a reasonable proxy for the basin's circa-1550 morphology.

To construct the current state, artificial systems (forest, agricultural, urban, and main industries) are spatialized along with the remaining patches of original ecosystems, based on land cover/use from CONAF 2021 (Table II.3).

4. Results

4.1. Reference and Current States

The Mapuche territory known as Lafken Mapu refers to the entire study area, located between the Biobío and Toltén rivers (Figure II.5) (Huenupil-Marihuen, et al., 2010). In 1550, native forest was the dominant ecosystem, covering 75% (7,661.4 km²) of the territory (Figure II.5a). It was mainly concentrated in the Nahuelbuta Mountain Range and experienced low levels of human intervention (Lara et al., 2012; Bengoa, 2000). The socio-ecological metabolism between people and native forests was linked to the diversity of flora found in the hills, which provided an abundance of resources such as hazelnuts or Chilean guava (Ugni molinae) (E8, 2021), fungi like digüeñe (E8,

2021), medicinal plants (Lahuen) used to treat imbalances in the body (illness) (E8, 2021), and wood for building houses, canoes, and domestic tools (Otero Durán, 2012). Even today, the hills are considered places for gathering and recreation, as well as areas of high ecological value (E1, 2021; E2, 2021; E8, 2021; E10, 2020). As stated by E10 (2020): "*It's the native forest that provides all the biodiversity, preserves water, and maintains the flora and fauna*". Today, remnants of native forest are mostly confined to higher elevations in the Nahuelbuta Mountain Range (Figure II.5b), especially near Nahuelbuta National Park (Figure II.3), a conservation area located at the highest point of the range. These remaining native forests cover a total of 2,553.8 km², which represents 24% of the total surface area.

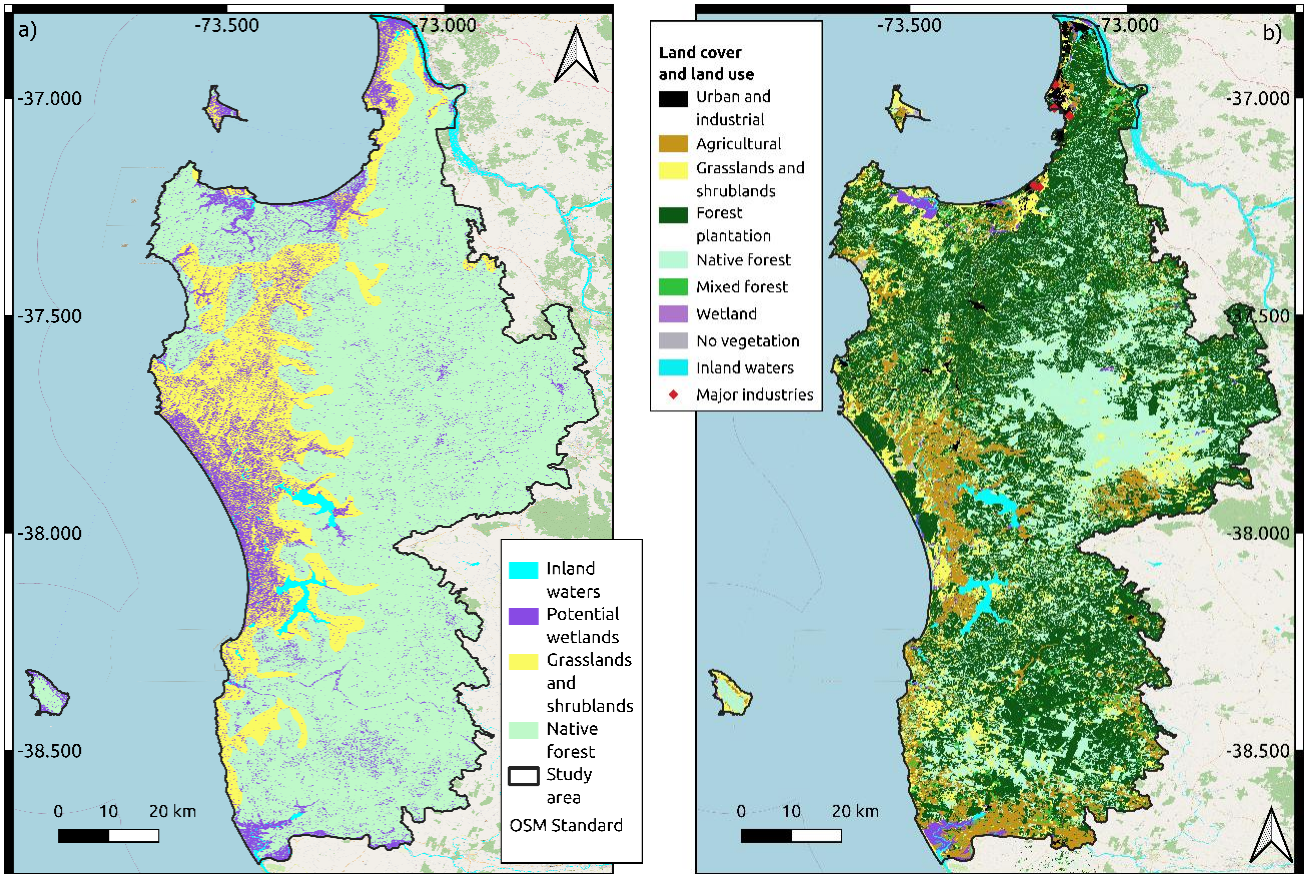


Figure II.5. Land cover/use: a) Reference map, circa 1550 (adapted from Lara et al. (2012)); b) Current map (2015–2024), based on CONAF 2021 cartography (IDE minagri, 2024). Source: own elaboration based on Lara et al. (2012) and CONAF (2021 data).

What occupies that area now? Figure II.5b visually displays the dominance of exotic forest plantations, primarily radiata pine and eucalyptus (Y. Zhao et al., 2016). "*You look ahead and it's all eucalyptus, eucalyptus, eucalyptus, and then harvested eucalyptus, young eucalyptus, mature eucalyptus, so from a visual perspective alone, there's an aspect that, let's say, is impossible not to notice*" (E10, 2022). According to the national land cover/use from CONAF 2021, 51% of the study area (5,209.75 km²) is currently covered by exotic forest plantations.

As shown in Figure II.5a, the extent of native forest is greater in the southern communes of Cañete, Contulmo, Tirúa, and Carahue—areas with a high percentage of Indigenous population (Table II.4, column 5). In other words, a visual correlation can be drawn between the concentration of native forest and the population type (Mapuche or non-Mapuche). This pattern dates back to the early days of Spanish colonization (Labraña-Muñoz & Arcas-Morales, 2006), when the northern area near Concepción became an urban center and point of penetration into the south, while the southern area was identified more as a zone of resistance. In the southern commune of Tirúa, for example, E10 (2021) explains: "*This territory has remained this way—with water reserves—because of the conflict with the State, the conflict between the Mapuche people and the State, where the Mapuche people or some communities have decided to preserve [...]. Here, forestry decreases or remains steady but doesn't advance, and there's also a political stance by local authorities, refusing to enter into so-called corporate social responsibility agreements [...], compensation is not accepted*." In short, the greater the Mapuche population, the fewer forest plantations, and the greater the biodiversity and water availability.

Table II.4. Communal social indicators (poverty index and percentage of Indigenous peoples) according to CASEN 2020 survey (BCNa, 2024). Population indicators (urban and rural population percentages) based on the 2017 Census (INEa, 2017). Rows have been sorted from north (San Pedro de la Paz) to south (Carahue), to evidence the north-south gradient in the indicators. Source: own elaboration based on CASEN 2020 survey and Census 2017.

Comuna	Income poverty rate	Percentage of indigenous peoples	Percentage of urban population	Percentage of rural population
San Pedro de la Paz	12,2	9,5	99,91	0,09
Coronel	13,8	11,8	98,03	2,74
Lota	14,4	12,1	99,8	0,3
Arauco	13,0	16,7	75,4	24,7
Lebu	17,3	28,2	92,0	8,1
Curanilahue	13,6	14,6	93,5	6,6
Los Álamos	16,9	27,1	89,02	10,98
Cañete	18,6	35,5	56,45	43,56
Contulmo	16,8	29,3	50,75	49,25
Tirúa	21,3	70,4	35,88	64,12
Carahue	22,9	40,9	54,1	46,0
Biobío Region	13,2	10,7	88,60	11,40
Country	10,8	12,4	87,80	12,20

While native forests occupied the higher areas of the territory by 1550, the lower areas were dominated by grasslands, shrublands, and wetlands, with a diffuse and shifting interface between these ecosystems. Grasslands and shrublands covered 2,516 km², which represented 24% of the total area. Today, they occupy only 11% (1,153.2 km²) of the studied territory. Agricultural areas, including intensive agriculture, in contrast, now cover 23% (2,411 km²) of the territory. There is also intensive and localized urban and industrial coverage that accounts for 0.01% (112 km²) of the total studied surface, concentrated in the northern area near the urban core.

In pre-colonial times, the abundance of natural resources allowed the development of a large-scale gathering system, complemented by hunting, livestock raising, and small- to medium-scale horticulture (Bengoa, 2000;

Otero Durán, 2012). One of the few estimates of the pre-colonial population suggests that between the Itata and Cruces rivers, there were around half a million inhabitants—an indication of relatively high population density. This suggests the existence of one or more well-structured social organizations (Bengoa, 2000). For small- and medium-scale livestock farming and agriculture, part of the original native forest—primarily in the lower parts of the basin—was cleared (Lara et al., 2012). Many of the grassland and shrubland ecosystems shown (Figure II.5a), are not native forest due to the human intervention of Mapuche people (Lara et al., 2012), indicating that significant environmental pressures had already altered the landscape in pre-colonial times (Bengoa, 2000). E8 (2021) reflects on this: "*The Mapuche didn't have hills, at least where I lived and was born, there were no hills, just 'vegas'*." These flood-prone areas—commonly known as vegas or wetlands—have long been recognized as fertile soils and sources of food and income, both in colonial and current times, especially when agricultural surpluses allow for selling (E1; E2; E8; Labraña-Muñoz & Arcas-Morales, 2006).

Traditional agricultural zones still persist. In rural areas in the southern part of the territory—and even within the urban core of Gran Concepción—mobile gardens still exist in the Los Batros Wetland: the Boca Sur gardens (Quevedo et al., 2022), a prime example of a biocultural patch (Castillo, n. d.). However, this traditional low-input agriculture (Maitra et al., 2021), long synchronized with seasonal flood and recession cycles, has been largely

replaced by intensive, dominant agriculture (Torres et al., 2015), characterized by extensive monocultures that require high levels of external inputs, such as fertilizers, pesticides, genetically selected seeds, and artificial irrigation. This causes ecological imbalances and soil degradation, making it an unsustainable practice (D. Sarkar et al., 2020). This type of agriculture contributes significantly to soil degradation, water pollution through chemicals, and erosion (Altieri & Rojas, 1999; Maitra et al., 2021).

Wetlands are typically found in topographically depressed areas (Gerding, 2010), as shown in Figure II.5a. They are recognized for their role in water purification and hydrological regulation (Hammer & Bastian, 1989) and often called the “kidneys” of the planet. They are globally acknowledged for housing traditional medicine used by 80% of the world’s population (Hu, Niu, Chen, et al., 2017; Mitra et al., 2003). In Mapuche culture, they are sacred areas called Menokos—places of connection with nature (E7, 2021) and refuges of biodiversity. The climate was a key factor influencing both soil productivity and the ecosystems present. The combination of heavy precipitation and local geology leads to the formation of the Nahuelbutan lakes, through natural drainage obstruction (Parra et al., 2003). Lakes and lagoons have long served as water reservoirs, community gathering spaces (E1, E2, E10), sources of direct water supply (E10), and food sources such as fish and birds (Bengoa, 2000). A portion of the precipitation flows as surface runoff,

while the rest infiltrates and is stored as groundwater and aquifers, slowly feeding watercourses even during the summer months (Szesztay, 1974).

Historically, communities in the region have settled based on water availability (Huenupil-Marihuen. et al., 2010), as E7 (2021) states: "*People used to build their homes near natural springs [...] or where the water table was high, so they could dig a well.*" In the traditional functioning of the territory, water was of sufficient quality that people could obtain it directly from ecosystems, as E10 (2022) recalls: "*You would go and get water straight from the river or water body*". Today, water is supplied through an intermediate human-managed step: urban water treatment plants and rural drinking water systems (APR), along with water trucks when water availability does not cover human basic needs.

Table II.5 summarizes the socio-ecological metabolism based on the original ecosystems shown in Figure II.5a, as well as the artificial ecosystems present today, as shown in Figure II.5b.

Table II.5. Summary of key original ecosystems (circa 1550) and artificial systems (2015-2024) identified in the territory, and the metabolism between them and human communities (socio-ecological metabolism). Source: own elaboration.

Vital element	Socio-ecological metabolism	Source
Native forest	Originally in a pre-Columbian state, the highlands were largely untouched by the Mapuche population, remaining covered by native forest. These areas have been recognized as abundant zones of high ecological value and a refuge for biodiversity. In them it is possible to find native tree species, fungi, fruits and water springs, as well as	E1, E2, E8, E10

	animals. Therefore, these ecosystems provided wood, food, medicine ("Lahuen") and water. Nowadays, the remnants of native forest in high areas of the Nahuelbuta Mountain Range allow this relationship with people, and are also recognized as spaces for social gatherings.	
Grasslands and shrublands	Wetlands have been sacred places and are recognized for their water purification role as "kidneys" of the territories. Because they are in low-lying areas prone to flooding, the soils used for agriculture and wetlands have a fuzzy boundary. The fertile soils of the area were ideal for vegetable cultivation in pre-Columbian times, with agricultural systems adapted to flooding that did not require major technologies. Lowland and wetland horticulture has been a source of economic livelihood since pre-colonial times, providing sustenance and surpluses to sell. Today, although not everyone has access to land for cultivation, those who do are able to develop small-scale home gardens.	E1, E2, E7, E8, Labraña-Muñoz & Arcas-Morales (2006).
Wetlands		
Lakes and lagoons	The lagoons and lakes have been reservoirs from which it was possible to access water for consumption. In addition, they have been a source of food through fishing and meeting and recreational spaces. Around them, fertile land has been used for agriculture.	E1, E2, E10, Labraña-Muñoz & Arcas-Morales (2006).
Watercourses, springs	The surface watercourses as well as the groundwater that originate in the Nahuelbuta Mountain Range are sites of direct water supply and define the territorial organization of human settlements.	E7, E10, Huenupil-Marihuen, et al. (2010)
Groundwater and aquifers	The Pacific Ocean and the coast have been an area abundant in food, as well as spaces for rest and recreation	
Intensive agriculture	The rapid growth of intensive agriculture was modulated by the export of agricultural products. Agriculture was modernized, taking the form of agricultural monocultures that require agrochemicals such as fertilizers and pesticides. The change in agricultural soil management produces erosion and soil degradation, which promotes premature aging of water bodies, accelerating eutrophication. Although this agriculture is dominant, there are still remnants of small-scale agriculture for subsistence and local sale.	E1, E2, E10 Altieri & Rojas (1999)

Forestry	Exotic forest plantations are the dominant land use in the study area. Their rapid economic expansion was promoted through a labor shift from agriculture to forestry. However, most of the production is exported, and the wealth generated does not result in improvements to local living conditions. These plantations are widely perceived as the main driver of environmental degradation, including native forest deforestation, drought, forest fires, and water pollution. Mitigation and compensation measures are limited, typically consisting of water trucks and rural drinking water systems (APR).	E1, E2, E10
Urban	Urbanization implies the impermeabilization of the land and is positioned as necessary for the growing population. Historically, mass population movements were modulated by industry, by the state through social housing, and in recent decades have been modulated by real estate companies. The differentiation of the type of housing, neighborhood and lifestyle proposed, especially by real estate companies, has led to the segregation of the population, giving added value to some sectors, with access to land through the courtyard, and not to others, where there is greater overcrowding. The occupation of former meeting areas has limited access to ecosystems such as hills or lakes/lagoons, fragmenting and privatizing the territory. Real estate developers have systematically filled in wetlands and replaced former horticultural areas. Urban areas generate waste that has historically been dumped into bodies of water, although today there is greater regulation.	E1, E2, E10

4.2. Anthropogenic Rift

The Spanish arrived to colonize the area in the 16th century, by founding cities in areas with little resistance and establishing forts in regions

where resistance was stronger. Concepción was founded in 1550 and became the gateway to the Araucanía region. Meanwhile, forts such as Arauco, Tucapel, and Purén were established (Labraña-Muñoz & Arcas-Morales, 2006). Since then, Concepción has served as the urban center from which the current territorial model was imposed, while the south remained a zone of resistance. However, by around 1600, the Spanish had withdrawn from the territory at the south of Biobío river, and this frontier remained unchanged until the Occupation of Araucanía (Huenupil-Marihuen et al., 2010). As shown in Figure II.6, the “environmental” history of the study area is marked by three major processes: (i) Occupation of Araucanía (1850–1880) (Fuentes-Hernández et al., 2024), which involved the displacement of the Mapuche people, the logging and burning of native forests, the opening of land for agriculture (Aguayo et al., 2009; Otero Durán, 2012), and the settlement of European colonists to work the land (Correa, 2021). (ii) Dictatorship in 1973 with implementation of neoliberal policies by the Chilean state, which accelerated the development of the forestry industry and intensive agriculture (Araya, 2019; Lara et al., 2012; Martínez Retureta, 2021). (iii) Urbanization, especially around Concepción since 1975, later modulated and accelerated from the 2000s onward (Rojas Quezada et al., 2009).

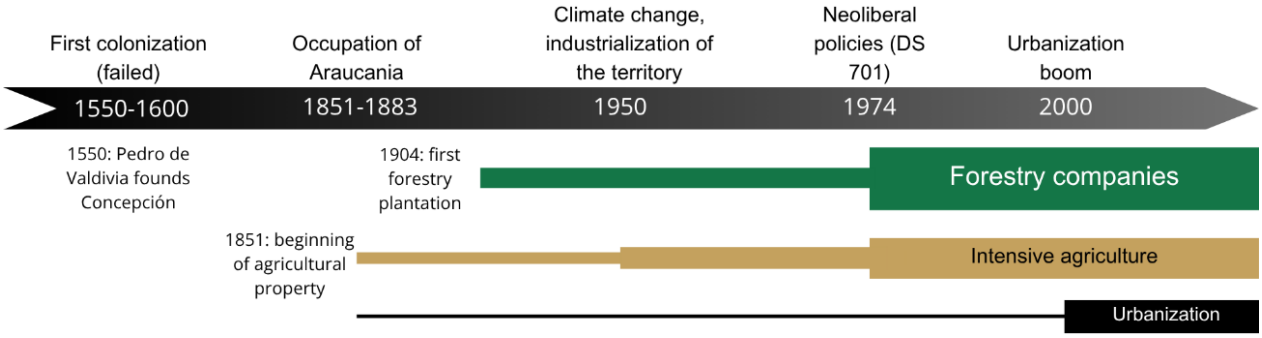


Figure II.6. Main milestones in the environmental history of the studied territory. Source: own elaboration.

4.2.1. Agriculture

As mentioned in Section 4.1. , by 1550 agricultural patches existed since pre-colonial times (grasslands and shrublands, Figure II.5a), constituting a significant alteration of the landscape (Bengoa, 2000). However, this was a form of low-input agriculture (Maitra et al., 2021). After a failed attempt of earlier colonization, the territory between the Biobío and Toltén rivers remained uncolonized and under Mapuche autonomy and jurisdiction from 1600 until 1850 (Correa, 2021). During the process: the Occupation of Araucanía, the Chilean State established legal frameworks to justify the displacement of Indigenous people into reduced spaces called “reducciones” or “títulos de merced” (Correa, 2021). Cities south of the Biobío River that had unsuccessfully attempted to establish themselves during the spanish colonization were reconstructed during this process (Huenupil-Marihuen. et al., 2010). In addition, the State carried out logging and burning of native

forests to open up land for agriculture (Aguayo et al., 2009; Otero Durán, 2012). Until the early 20th century, European settlers arrived to work the land (Correa, 2021), consolidating the agricultural character of the territory through land ownership integrating it into the Chilean agrarian society that formed since the colonial period (Llorca-Jaña et al., 2017). A few years later, in 1889, the deforestation of native forests and the dispossession of Mapuche lands led to soil erosion, which hindered the full development of agriculture and served as the basis to justify the implantation of exotic forest plantations (Torres et al., 2022).

By 1974, a process of neoliberal policy implementation began, promoting exportation to global markets and marking the transition from traditional to intensive agriculture (Torres et al., 2015), characterized by monocultures that depend heavily on agrochemical inputs (Altieri & Rojas, 1999), require reliable irrigation and high-quality seeds (Maitra et al., 2021), and make use of various technologies (Torres et al., 2022).

The historical process of agricultural intensification, marked by territorial dispossession and soil degradation, constitutes a key mechanism of the anthropogenic rift described in this study.

4.2.2. Exotic Forest Plantations

Forest plantations were introduced and used under several governments in Chile as a strategy to combat the soil erosion resulting from

the deforestation of 1889 (Torres et al., 2022). From the 1950s onward, the Chilean State promoted industrialization along the coastal edge of the territory through the establishment of private industries and new technologies (Torres et al., 2015; Y. Zhao et al., 2016). This influenced urban development by drawing in workers and their families, particularly to the urban hub near Concepción (Torres et al., 2015).

In 1974, forest plantations and the forestry industry received renewed support as a key driver of economic growth, promoted by the Chilean State and CORFO through Decree Law 701 (Aguayo et al., 2009; Echeverría et al., 2014). At this point, many agricultural properties created during the Occupation of Araucanía were sold to forestry companies (Correa, 2021; Heilmayr et al., 2016). Traditional rural agriculture declined (Carmona & Nahuelhual, 2012; Ortiz et al., 2024), as labor shifted into other sectors. "*Mainly men started leaving peasant agriculture to enter the forestry industry—in various roles such as chainsaw operators, contractors, drivers, and so on*" (E10, 2022). At the same time, land cover changed, as traditional agricultural patches and native forests—especially the untouched ones in the Nahuelbuta Range—were converted into forest plantations (Aguayo et al., 2009).

There was a perception of economic growth and improving living conditions. "*It was seen as more money, more regularly, money in circulation became more common*" (E10, 2022). The forestry industry shaped urban and territorial dynamics (Barros Delgado, 2022) and positioned itself as one of the

main sources of employment in the area and one of the most significant economic activities in the country, contributing approximately 3.4% of the national GDP (Banco Central de Chile, 2025). In 2013, it ranked as the second-largest natural resource-based export sector after mining (INFOR, 2014). Five countries receive around 55% of total forestry exports, with the main destinations being China, the United States, and Japan (INFOR, 2014; Y. Zhao et al., 2016).

Despite all this, many of the municipalities dominated by forest plantations are among the poorest, not only in comparison to their respective regions but also nationwide (Table II.4). The municipalities in the study area generally have higher poverty rates than the regional average, and all have higher poverty rates than the national average. The highest poverty rates are found in the municipalities with the greatest proportions of Indigenous populations, revealing the historical Mapuche conflict.

The historical expansion of exotic forest plantations, promoted by state policies and global markets, caused structural changes in both landscape and labor, displacing both native forests and traditional forms of subsistence, homogenizing the territory.

4.2.3. Urbanization and Industry

As seen in Sections 4.2.1. and 4.2.2. , urbanization has historically been shaped by industry. Figure II.7 shows a differentiation in the communal

demographic pattern. Population growth in the northern area (San Pedro de la Paz, Coronel, Lota), near the Biobío River, has been explosive, originating from the colonial formation of the city of Concepción (see Figure II.7), the development of the coal industry (Labraña-Muñoz & Arcas-Morales, 2006), and subsequent industrial development promoted by the Chilean State (Torres et al., 2015). Meanwhile, in the central and southern area of the study region (Arauco, Lebu, Curanilahue, Los Álamos, Cañete, Contulmo, Tirúa, Carahue), population dynamics show slower growth and have partly followed the trajectory of the coal industry and later the forestry industry (Barros Delgado, 2022).

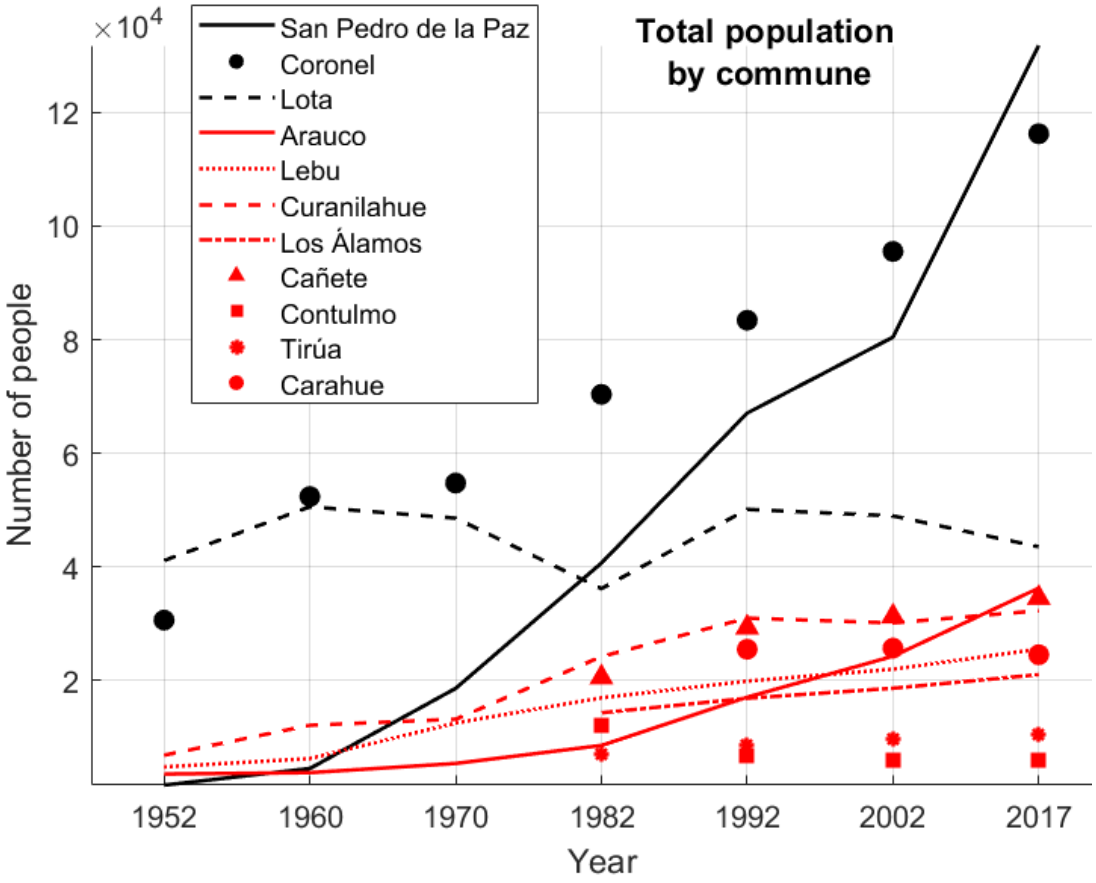


Figure II.7. Total population by commune of the study area, according to Chilean censuses from 1952 to 2017 (BCNb, 2017; BCNc, 2024; INEa, 2017; INEb, 2024). Source: own elaboration based on INE (2017, 2024) and BCN (2002, 2017).

During the colonial era, the San Pedro de la Paz area was established as a nascent urban center associated with Concepción (Labraña-Muñoz & Arcas-Morales, 2006). It was a region of fertile lands where subsistence farming and livestock rearing were practiced, with lakes for fishing and abundant water, generating surpluses that were sold in Concepción (Labraña-Muñoz & Arcas-Morales, 2006). In the 1960s, urbanization in San Pedro de la Paz, recognized as “bedroom of Concepción”, was promoted by the State due

to a shortage of suitable housing land in Concepción. Its growth accelerated with the construction of road infrastructure such as bridges and routes (Labraña-Muñoz & Arcas-Morales, 2006). Today, the main driver of urbanization is real estate development and the construction of social housing since the 1970s (Labraña-Muñoz & Arcas-Morales, 2006; E1, 2021). The spatial location of a given area defines whether it has higher or lower property values. Higher values are associated with the lakes, resulting in the formation of high-income neighborhoods around them (E1, 2021; E2, 2022). This type of development has segregated the area, resulting in high levels of inequality, especially in the municipality of San Pedro de la Paz, which has the second-highest Gini index in Chile (0.541), making it the second most unequal municipality in the country (Suazo, 2014). Ecologically, urban development occurs through the filling of wetlands. This is a global problem and the leading cause of wetland loss (Davidson et al., 2018; Fluet-Chouinard et al., 2023).

The municipalities of Lota and Coronel began to grow in population as early as 1840, when coal exploitation began in the Gulf of Arauco and promoted by the Chilean State as key to the region's development (Labraña-Muñoz & Arcas-Morales, 2006). For many decades, the region was structured around coal. Infrastructure was built to facilitate the arrival of coal workers and their families, and industries dependent on coal supply were established, giving the area a local industrial character (E4, 2022).

However, despite the coal industry, small fishing communities continued to subsist. The problem arose in the 1990s, when coal activity declined, triggering an economic crisis that was partially offset by the migration of industries from Talcahuano to Coronel and the construction of one of the largest ports in Chile (Pinto et al., 2023), which led to the privatization of the coastal edge. Today, the city has a high concentration of industries, an industrial park, and three thermoelectric power plants (closed due to their environmental impact), as well as fragmentation through a wall that denies people access to the sea (Bravo Ferretti et al., 2022). Urban and industrial expansion, driven by extractive and segregating logic, has failed to improve the quality of life for local communities. On the contrary, it has intensified the disconnection between people and their ecosystems, accelerated wetlands loss, fragmented the territory, and exacerbated socio-spatial inequality. This process has replaced biocultural landscapes with high-impact infrastructure, consolidating a new socio-ecological metabolism that is disconnected from ecological cycles.

5. Discussion

The pristine ecosystems that still exist today are the result of thousands of years of adjustment (Kay & Schneider, 1995; Upreti, 2023). They are resilient, meaning they can return to their original state in the face of a “normal” disturbance (Regier, 1993a). When a disturbance exceeds normal frequency

and intensity ranges, the system may shift to a new state of equilibrium while still exhibiting resilience (Holling, 1986). It is reproduced through political, economic, social, cultural, and ecological structures. Through these structures, efforts were invested to bring about a socio-natural state change from its original condition. Environmental management is thus justified as a means to transition toward another state (Mayer & Rietkerk, 2004). Defining reference and current states is necessary to envision potential restoration processes.

This study constructs a reference state for the studied territory, in the pre-colonial period around 1550, which would have remained relatively stable until 1850. We also define the current situation (2015–2024). Acknowledging the depth of the issue, we go beyond land cover analysis, integrating it with the socio-ecological metabolism. This innovative interdisciplinary approach helps dissolve the perceived boundary between culture and nature, society and ecology. We were able to address socio-ecological degradation—both a complex global issue and a historically rooted local problem with a strong political component—with a depth that would not have been possible under a disciplinary lens.

Due to the scarcity of spatial information at such an early time (1550-1850), in the study area there is only the work of Lara et al. (2012), which divides the territory into: i) native forest and ii) grasslands and shrublands. We added a third class to this work: wetlands, through the concept of potential wetlands. As there is no high-resolution database for this layer available in

Chile, this work constitutes a contribution as a relevant new source of spatial data.

The empirical and theoretical findings in this work confirm the hypothesis of a cumulative anthropogenic rift in the Nahuelbuta region, reflected in the loss of ecological integrity and functional disconnection between communities and their ecosystems. These findings contribute to proving the hypothesis 1 of the present doctoral thesis, and to achieving the specific objective 1. The pre-Columbian state has natural/cultural integrity (Regier, 1993a) characterized by an abundant nature, due to the rainy climate and fertile soils, which allows the availability of water, food, medicine and materials directly from nature, capable of sustaining a large population, larger than that of typical pre-agrarian societies of the time (Bengoa, 2000). The dominant relatively non-altered native forest covered 75% of the territory. The environmental pressure exerted by the Mapuche communities in lowlands was represented through the transformation of 24% of the native forest into grasslands and scrub. This state is strongly driven by the Mapuche worldview, and in general, by indigenous people globally, which emphasizes the intrinsic value assigned to Nature and the understanding reflected by E7 (2021): "the culture of indigenous peoples says, we are part of nature". There are still remnants of this, but in smaller quantities.

On the other hand, the current state of the territory presents severe degradation of ecosystems, which is manifested in the scarcity of fertile land,

food, quality and quantity of water (Alaniz et al., 2022; Fuentes et al., 2021) and recently, the devastating mega-fires (Carmona & Nahuelhual, 2012; Ortiz et al., 2024). The main mechanisms have been dispossession, land occupation and neoliberal public policies (Bengoa, 2000; Correa, 2021), all of which have defined the dominant land uses, to whom the land belongs (ownership) and land management practices (socio-ecological metabolism). These mechanisms have taken place in three key historic milestones: the Spanish colonization (1553), the Occupation of the Araucanía Region (1881), and the Dictatorship in 1973. Landscape consequences are the decrease of the original native forests to 24%, while agricultural areas inside grasslands and shrublands have diminished to 11%. In parallel, exotic forest plantation has expanded, occupying today 51% of the territory, followed by agriculture and intensive agriculture that now occupies 23%.

This new metabolism has been driven by economic development, justified by the promise of better living conditions. But territorial decisions are made through centralized power. This territory is sacrificed locally for an improvement at the national level. In an extreme case, it is called Sacrifice zone, such as the case of Coronel (E1, E10). Thus, economic growth is prioritized at the expense of social and ecological sustainability (E1, E10) through an extractivist economy (E1, 2021).

The impacts are related to a fundamental element: the relationship with water. Originally, access to water was provided by nature to people and

ecosystems (E8, E10). It is nature that possessed the water. In the current state, people no longer rely directly on nature for water but depend on an intermediary management system, such as the RWA or water treatment infrastructure (E10). In this case, water ownership is assigned to some people. Sometimes, they are managed by the forestry industry as mitigation and compensation measures. Locally recognized impacts are the fragmentation of the territory (E1, E2), privatization that no longer allows access to ecosystems (E1, 2021; E2, 2022; E4, 2022), forest hegemony (E10, 2022; E7, 2021) or major industries that even affect people's health (E4, 2022; Bolados et al., 2024). The political structures that reproduce the current state are public policies that promote certain land uses that replace the original natural infrastructure of the territories (e.g., Decree 701); the leniency of the State and local authorities toward industry, for example, through territorial planning instruments (E1, E2, E10); or education that does not transmit Mapuche knowledge (E8).

There is a well-documented relation between land cover/use and socio-ecological metabolism with the water cycle, regarding its quantity and quality. The transition from a native forest, wetland and low input agriculture to exotic forestry plantation, intensive agriculture and expanding urban/industrial areas plausibly modifies water quantity by changing how precipitation is partitioned into runoff and infiltration/groundwater storage (Martínez Retureta, 2021). It also affects water quality through enhanced erosion and sediment delivery and

the mobilization of agrochemical inputs (Lee et al., 2023; Parra et al., 2003). In parallel, wetland loss and degradation reduce both storage and the “kidney” function of wetlands in filtering water (Hammer & Bastian, 1989). Together, these pathways provide a causal bridge from the H1 landscape and metabolic rift to the H2 expectation of measurable impacts on water availability and quality in the territory that will be explored in the next chapters.

It will not be possible to exactly reproduce the original situation of 1550. At the global and local level, conditions have changed: the world population has multiplied, the world is globalized and interconnected (Lewis & Maslin, 2015) and unequal climate change is present, creating new baseline conditions that disproportionately affect developing countries (Sultana, 2022). Restoration will move the system to a new state of integrity. We propose the emerging restoration approach: socio-ecological restoration (Tedesco et al., 2023), which aims to restore interdependent processes in a socio-ecological system (Fernández-Manjarrés et al., 2018), with multiple dimensions (Voulvoulis et al., 2022). Moreover, in places where the political dimension has driven the socio-environmental conflicts, such as the present case study, transformative socio-ecological restoration implies addressing the conflict (Carrasco Henríquez & Mendoza Leal, 2021; Tedesco et al., 2023), which further justifies our historical approach. Integrating values, practices and knowledge, in addition to ecological restoration, enables transformations that

lead to benefits for people and nature in the long term, through resilience (Tedesco et al., 2023).

Now, when we talk about restoration, we commonly think of land use restoration, such as planting native trees. But this marginalizes the intrinsic potential of nature to heal, and the indigenous and sustainable practices that facilitate this process. One approach to restoration—natural recovery—involves addressing the key anthropogenic drivers of social-ecological degradation (Chazdon et al., 2024), which in the study area are forestry, agriculture, fishing and urbanization. In this context, Mapuche resistance to the entry of anthropogenic forcing described in Section 4.2.2. emerges as a biocultural conservation strategy (Aróstegui, 2001; Carrasco Henríquez & Mendoza Leal, 2021; Torres et al., 2015) safeguarding nature and allowing it to express its self-healing potential.

In this context, three lines (I, ii and iii) of action for socio-ecological restoration are proposed, as detailed below.

i) Address socio-environmental conflicts, particularly the Mapuche conflict, understanding that is at the roots of the conflict, and is an important part of the current forestry conflict. The magnitude of the conflict is reflected in the fact that on October 21 of 2021, the right-wing Government of Piñera decreed a State of Exception for the country's Macrozona Sur (Southern Macrozone), which included the Biobio and Araucania regions where most

Mapuche people live, authorizing Armed Forces to support to public security (Biblioteca del Congreso Nacional, 2021; Torres, 2023). This situation reduces the spaces of democracy (Gudynas, 2014). To tackle this conflict, the left-wing Government of Boric organized a commission with different stakeholders to reach an agreement and reduces the conflict (Comisión Presidencial para la Paz y el Entendimiento, 2025). This commission identifies the lack of recognition, the historical loss of land, and the insufficient response to reparation demands as the main causes of the conflict between the State, forestry corporations, and the Mapuche people. It highlights the socioeconomic lag of the regions of Biobío, Araucanía, Los Ríos and Los Lagos, which contain the poorest municipalities in Chile. It points to D.S. 701 and the creation of protected wilderness areas as aggravating factors of the conflict. The report also states that the current institutional framework (Law No. 19.253 of 1993 and the creation of the National Corporation for Indigenous Development (CONADI)) does not respond to current demands. It presents 21 recommendations, among which are the constitutional and cultural recognition of the Mapuche people, access to and control of land, the harmonious territorial coexistence between the Mapuche people and the forestry industry, and the need for reparation for the people adversely affected for living in an area of conflict.

ii) Stop the drivers of degradation, through regulation and control of intensive extractive activities, which can be achieved through legal instruments

such as the Urban Wetlands Law, the NSCA or the recent Law for the Nature (21.600). In this way, the intrinsic potential of Nature to heal itself, once degradation is stopped, is recognized and activated. In general, work should proceed on two fronts. The first is to reduce intensive use to a spatial extent, taking the watershed as the unit of analysis, ensuring an adequate distribution of intensive uses and avoiding overloading one watershed to the detriment of others. The second is to make intensive uses less intensive, giving anthropic systems greater diversity at the landscape scale. An important theoretical framework to follow in these cases is multifunctional landscapes, in this case, multifunctional land use. For example, the multifunctional forest landscape, which seeks to respond simultaneously to economic demands (timber production) and to ecological and social demands on forests (biodiversity conservation, recreation, ecosystem services, cultural and spiritual values) (Schmithuesen, 2007). Applied to urban areas, the concept of multifunctionality involves urban planning, ecosystem services, sustainability and climate adaptation. To achieve this, elements such as spatial distribution, accessibility and social participation must be addressed (Korkou et al., 2023). In the context of agriculture, when it is multifunctional, besides producing, it manages resources, conserves landscapes/biodiversity and sustains rural economies (Renting et al., 2009). There are even extensions to the urban–agricultural interface (Lovell, 2010) or to agroforestry/agricultural–forestry systems (Cheng et al., 2024; Y. Guo et al., 2023).

iii) Preserve and restore areas of socio-ecological value and biocultural patches, understanding them as areas that reproduce a socio-ecological metabolism that sustains the integrity of the system and where people's organic linkages with nature reside. Socio-ecological restoration implies multidimensional restoration. In the economic sphere, this involves granting access to and control over ecosystems and their resources, which implies the possibility of generating income through local practices, thus addressing the socioeconomic lag in the area compared to the rest of the country. For example, in fishing coves (caletas), strengthening small-scale, non-intensive artisanal fishing or seaweed gathering (E1, 2021).

Locally, solutions emerge such as the rescue of local economies (E1, 2021) local history (E5, 2022) or biological corridors (E1, 2021). For example, according to (E1, 2021) in the case of San Pedro de la Paz, the lagoons are beautiful landscapes connected to the wetland Los Batros (Municipality of San Pedro de la Paz, 2019), where traditional horticulture is developed. This ecosystem ends at Caleta Alto del Rey in Boca Sur, with abundant marine products (Caro, 2003). However, this biocultural corridor is threatened by the road infrastructure associated with the "Industrial Bridge", a private project associated with the forestry industry. In this context, the need to frame development and articulate all efforts under a socio-ecological restoration approach is imminent. This strategy should recognize the flow of matter and

energy from the mountains to the sea, that forms interconnected biocultural corridors.

Some of the State solutions proposed are the Urban Wetlands Law, Marine Coastal Spaces for Native Peoples (ECMPO) (Araos et al., 2023), protected areas, Nature Sanctuaries, Intangible Cultural Heritage, among others. In addition, a project was also implemented in the area, the Program for the Recovery of Environmental Services of the Ecosystems of the Arauco Province (PRELA), which laid the groundwork for the creation of a secondary environmental quality standard (NSCA), working groups with social actors, transition activities towards sustainable agricultural practices, restoration and environmental education.

However, in general, there have been inconsistencies and contradictions within the socio-ecological recovery process. Some reports indicate instances of misused legal frameworks originally designed to safeguard ecosystems and their people (Iturra Urzúa, 2024; Paredes & Ulloa, 2021). Balancing economic development with the protection of biocultural systems is one of the greatest challenges for States. We hope that this work will contribute to the reconciliation of both aspects.

6. Conclusion

To gather relevant information for ecological restoration, this study analyzes the change of state in the Nahuelbuta mountain range in southern Chile, along with the adjacent communes on its western flank. The environmental history analysis of the territory as a socio-ecological system reveals degradation through loss of ecological integrity from the mid-16th century to the present. Based on the analysis of socio-ecological metabolism and land cover/use, we define two distinct territorial states. The first is a reference state in the pre-Columbian period (1550) but likely sustained until around 1850. In this state, human communities interacted with the landscape through traditional practices and knowledge systems grounded in the recognition of nature's intrinsic value and a strong relational connection to it. Environmental pressure was concentrated in the lowland areas, where agricultural systems adapted to flood-prone wetlands coexisted with small-scale livestock practices. Native forests extended across the Nahuelbuta mountain range, acting as reservoirs of biodiversity and water, sources of medicine, food and timber. Despite localized environmental pressures, the territory at this time exhibited a condition of natural and cultural integrity. People had complete control and access to ecosystems.

During the Spanish colonization (1553), the territorial structure that we know today began to take shape, with the formation of Concepción as an urban

center and forts to the south. However, the profound change did not begin until the Occupation of Araucanía in 1850, where indigenous communities were dispossessed and settlers implanted. Later, since 1973, during the military dictatorship, a series of public policies were promoted that resulted in the expansion of forestry plantations, intensive agriculture, urbanization near Concepción. Under the vision of Nature as provider of goods and services and a logic of extractivism, privatization and land exploitation which, compounded by the effects of climate change, transformed the territory from an intact to a degraded state (current), characterized by contamination and scarcity of water and food, socio-environmental conflicts, no control and access over ecosystems, poverty and notably the recent mega forest fires.

Together, the empirical and theoretical findings presented here confirm the hypothesis of a cumulative anthropogenic rift around the Nahuelbuta region, marked by a profound loss of ecological integrity and a functional disconnection between communities and their ecosystems. We conclude that it is necessary to address the multiple dimensions of degradation: social, cultural, economic, ecological, and especially the one that caused the main change in the territory studied: politics. This suggests a socio-ecological restoration approach, a theoretical framework under which three key elements are envisioned: (i) address the Mapuche conflict, understanding that the problem originated for political reasons, (ii) stop the drivers of degradation by

recognizing nature's potential to heal, and (iii) preserve and restore biocultural landscapes and those places with socio-ecological value.

This study not only provides a historical-ecological framework to understand this transformation but also advances a restorative vision grounded in environmental justice. Overcoming this rupture and moving toward sustainable futures requires addressing both colonial legacies and contemporary extractivism through integrated, territory-based strategies centered on communities, and their knowledge.

Declaration of Interest Statement: The authors declare that there are no known financial, professional, or personal conflicts of interest that could have appeared to influence the work reported in this thesis.

Acknowledgements: We appreciate the participation of the people interviewed, who provided valuable insights and knowledge. We thank Dr. Cristian Echeverría for kindly providing the spatial dataset of the Nahuelbuta Mountain Range, which was fundamental to the delineation of the study area.

Funding: The first author is thankful for the financial support from Ph.D scholarship ANID BECAS/DOCTORADO NACIONAL 21212143. We acknowledge the financial support of the projects: ANID/FONDECYT-Iniciación/11230469 and ANID/FONDAP/1523A0001, for the valuable contribution of translation and proofreading.

Data availability statement: All datasets used in this study are publicly available and have been properly cited throughout the manuscript. The corresponding websites and repositories from which the data were obtained are indicated in each referenced section. The interviews conducted as part of this research are also available upon reasonable request to the corresponding author, in accordance with ethical and confidentiality considerations.

References

Abarca-Del-Rio, R., CrÉtaux, J.-F., Berge-Nguyen, M., & Maisongrande, P. (2012). Does Lake Titicaca still control the Lake Poopó system water levels? An investigation using satellite altimetry and MODIS data (2000–2009). *Remote Sensing Letters*, *3*(8), 707-714. https://doi.org/10.1080/01431161.2012.667884

Abarzúa et al. (2020). *Informe final: Análisis de Testigo Sedimentari... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Informe%20final%3A%20An%C3%A1lisis%20de%20Testigo%20Sedimentario%20en%20Lago%20Lanalhue%2C%20Provincia%20de%20Arauco%2C%20Regi%C3%B3n%20del%20Biob%C3%ADo&author=A.M.%20Abarz%C3%BAa&publication_year=2020

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, *5*(1), 170191. https://doi.org/10.1038/sdata.2017.191

Abubakar, H. B. (2024). *Evaluation of high-resolution precipitation datasets CHIRPS, TerraClimate and TAMSAT over the Enkangala Escarpment of South Africa*. Research Square. https://doi.org/10.21203/rs.3.rs-4365508/v1

Adjovu, G. E., Stephen, H., James, D., & Ahmad, S. (2023). Overview of the Application of Remote Sensing in Effective Monitoring of Water Quality Parameters. *Remote Sensing*, *15*(7), 1938. https://doi.org/10.3390/rs15071938

Afsharian, S., & Taylor, P. A. (2019). On the Potential Impact of Lake Erie Wind Farms on Water Temperatures and Mixed-Layer Depths: Some Preliminary 1-D Modeling Using COHERENS. *Journal of Geophysical Research: Oceans*, *124*(3), 1736-1749. https://doi.org/10.1029/2018JC014577

Agência Nacional de Águas. (2010). *NORMAS DE COBRANÇA PELO USO DE RECURSOS HÍDRICOS*. https://www.ana.gov.br/arquivos/institucional/sge/CEDOC/Catalogo/2010/NormasDeCobrancaPeloUsoDosRecursosHidricos2010.pdf

Agência Nacional de Águas e Saneamento Básico (ANA). (2025). *Qualidade da água*. https://www.gov.br/ana/pt-br/assuntos/monitoramento-e-eventos-criticos/qualidade-da-agua/qualidade-da-agua

Aguayo Arias, M. I. (2008). *El cambio de uso del suelo en el centro sur de Chile. Comprendiendo su dinámica a través de la modelación espacialmente explícita y explorando sus efectos ambientales en una cuenca hidrológica de meso escala.* [[PhD Thesis], Universidad de Concepción]. https://repositorio.udec.cl/handle/11594/6004

Aguayo, M., Pauchard, A., Azócar, G., & Parra, O. (2009). Cambio del uso del suelo en el centro sur de Chile a fines del siglo XX: Entendiendo la dinámica espacial y temporal del paisaje. *Revista chilena de historia natural*, *82*(3), 361-374.

Alaniz, A. J., Abarzúa, A. M., Martel-Cea, A., Jarpa, L., Hernández, M., Aquino-López, M. A., & Smith-Ramírez, C. (2021). Linking sedimentological and spatial analysis to assess the impact of the forestry industry on soil loss: The case of Lanalhue Basin, Chile. *CATENA*, *207*, 105660. https://doi.org/10.1016/j.catena.2021.105660

Alaniz, A. J., Smith-Ramírez, C., Rendón-Funes, A., Hidalgo-Corrotea, C., Carvajal, M. A., Vergara, P. M., & Fuentes, N. (2022). Multiscale spatial analysis of headwater vulnerability in South-Central Chile reveals a high threat due to deforestation and climate change. *Science of The Total Environment*, *849*, 157930. https://www.sciencedirect.com/science/article/pii/S004896972205029X

Albus, K. H., Thompson, R., Mitchell, F., Kennedy, J., & Ponette-González, A. G. (2020). Accuracy of long-term volunteer water monitoring data: A multiscale analysis from a statewide citizen science program. *PLOS ONE*, *15*(1), e0227540. https://doi.org/10.1371/journal.pone.0227540

Alfonso, L., Gharesifard, M., & Wehn, U. (2022). Analysing the value of environmental citizen-generated data: Complementarity and cost per observation. *Journal of Environmental Management*, *303*, 114157. https://doi.org/10.1016/j.jenvman.2021.114157

Allan, M. G., Hamilton, D. P., Trolle, D., Muraoka, K., & McBride, C. (2016). Spatial heterogeneity in geothermally-influenced lakes derived from atmospherically corrected Landsat thermal imagery and three-dimensional hydrodynamic modelling. *International Journal of Applied Earth Observation and Geoinformation*, *50*, 106-116. https://doi.org/10.1016/j.jag.2016.03.006

Almanza, V., Parra, O., De M. Bicudo, C. E., Baeza, C., Beltran, J., Figueroa, R., & Urrutia, R. (2016). Occurrence of toxic blooms of Microcystis aeruginosa in a central Chilean (36° Lat. S) urban lake. *Revista Chilena de Historia Natural*, *89*(1), 8. https://doi.org/10.1186/s40693-016-0057-7

Altieri, M. A., & Rojas, A. (1999). Ecological Impacts of Chile's Neoliberal Policies, with Special Emphasis on Agroecosystems. *Environment, Development and Sustainability*, *1*(1), 55-72.

Altman, D. G. (1990). *Practical Statistics for Medical Research*. Chapman and Hall/CRC. https://doi.org/10.1201/9780429258589

Alvial Vásquez, F.-J., Abarca-del-Río, R., & Ávila, A. I. (2020). High-Resolution Precipitation Gridded Dataset on the South-Central Zone (34° S–41° S) of Chile. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.519975

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M., Moghaddam, S. H. A., Mahdavi, S., Ghahremanloo, M., Parsian, S.,

Wu, Q., & Brisco, B. (2020). Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 5326-5350. https://doi.org/10.1109/JSTARS.2020.3021052

Amour, I., & Kauranne, T. (2017). A variational ensemble Kalman filtering method for data assimilation using 2D and 3D version of COHERENS model. *International Journal for Numerical Methods in Fluids*, *83*(6), 544-558. https://doi.org/10.1002/fld.4276

Angrosino, M. (2012). *Etnografía y observación participante en Investigación Cualitativa*. Ediciones Morata.

Araos, F., Catalán, E., Nuñez, D., Riquelme, W., Cortinez, V., de Fina, D., & Anbleyth-Evans, J. (2023). Cuidando la Patagonia Azul: Prácticas y estrategias de los pueblos originarios para curar las zonas marinas del sur de Chile. *The Journal of Latin American and Caribbean Anthropology*, *28*(4), 286-297. https://onlinelibrary.wiley.com/doi/abs/10.1111/jlca.12695

Araya. (2019). *Desafíos del turismo y la conservación de la biodiversidad* (Primera edición, septiembre de 2019). Amukan Editorial itinerante.

Ardiantiono, Deere, N. J., Seaman, D. J. I., Mamat Rahmat, U., Ramadiyanta, E., Lubis, M. I., Trihangga, A., Yasin, A., Alza, G., Sari, D. P., Daud, M., Abdullah, R., Mutia, R., Melvern, D., Tarmizi, Supriatna, J., & Struebig, M. J. (2025). Improved cost-effectiveness of species monitoring programs through data integration. *Current Biology*, *35*(2), 391-397.e3. https://doi.org/10.1016/j.cub.2024.11.051

Argyilan, E. P., & Forman, S. L. (2003). Lake Level Response to Seasonal Climatic Variability in the Lake Michigan-Huron System from 1920 to 1995. *Journal of Great Lakes Research*, *29*(3), 488-500. https://doi.org/10.1016/S0380-1330(03)70453-5

Aróstegui, M. G. (2001). Cultura de la resistencia. Concepciones teóricas y metodológicas para su estudio. *Islas*, (127), 20-41. http://islas.uclv.edu.cu/index.php/islas/article/download/721/646

Arroyo, M. T. K. (2006). *El hotspot chileno, prioridad mundial para la conservación. Diversidad de ecosistemas, ecosistemas terrestres*.

Arsen, A., Crétaux, J.-F., Berge-Nguyen, M., & Del Rio, R. A. (2014). Remote Sensing-Derived Bathymetry of Lake Poopó. *Remote Sensing*, *6*(1), 407-420. https://doi.org/10.3390/rs6010407

Ascencio, E., Rivera, P., Cruces, F., Vila, I., Ascencio, E., Rivera, P., Cruces, F., & Vila, I. (2018). Estudio morfológico de Naiadinium polonicum (Dinophyceae) reportado por primera vez en aguas continentales de Chile. *Gayana. Botánica*, *75*(1), 438-446. https://doi.org/10.4067/S0717-66432018000100438

Assumpção, T. H., Popescu, I., Jonoski, A., & Solomatine, D. P. (2018). Citizen observations contributing to flood modelling: Opportunities and challenges. *Hydrology and Earth System Sciences*, *22*(2), 1473-1489. https://doi.org/10.5194/hess-22-1473-2018

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., Van Den Hurk, B., Hirschi, M., & Betts, A. K. (2009). A Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System. *Journal of Hydrometeorology*, *10*(3), 623-643. https://doi.org/10.1175/2008JHM1068.1

Banco Central de Chile. (2025). *Base de Datos Estadísticos (BDE)*. https://si3.bcentral.cl/siete/ES/Siete/Cuadro/CAP_CCNN/MN_CCNN76/CCNN_EP18_05_ratio

Baracchini, T., Hummel, S., Verlaan, M., Cimatoribus, A., Wüest, A., & Bouffard, D. (2020). An automated calibration framework and open source tools for 3D lake hydrodynamic models. *Environmental Modelling & Software*, *134*, 104787. https://doi.org/10.1016/j.envsoft.2020.104787

Barría, P., Chadwick, C., Ocampo-Melgar, A., Galleguillos, M., Garreaud, R., Díaz-Vasconcellos, R., Poblete, D., Rubio-Álvarez, E., & Poblete-Caballero, D. (2021). Water management or megadrought: What caused the Chilean Aculeo Lake drying? *Regional Environmental Change*, *21*(1), 19. https://doi.org/10.1007/s10113-021-01750-w

Barros Delgado, B. B. J. (2022). *Dinámica de los asentamientos rurales y su relación con la expansión forestal en las comunas de Curanilahue, Lebu y Los Álamos, entre el periodo 1960—2002*. https://repositorio.uchile.cl/handle/2250/188639

Batina, A., & Krtalić, A. (2024). Integrating Remote Sensing Methods for Monitoring Lake Water Quality: A Comprehensive Review. *Hydrology*, *11*(7), 92. https://doi.org/10.3390/hydrology11070092

BCN. (2024). *Biblioteca del Congreso Nacional de Chile. Glosario de términos geográficos*. https://www.bcn.cl/siit/glosario/index_html

BCNa. (2024). *Reporte Comunal—Biblioteca del Congreso Nacional de Chile*. https://www.bcn.cl/siit/reportescomunales/comunas_v.html?anno=2023&idcom=8108

BCNb. (2017). *Buscador Estadístico—SIIT*. https://www.bcn.cl/siit/estadisticasterritoriales//resultados-consulta?id=326233

BCNc. (2024). *Chile: Población censada y tasas de crecimiento medio anual, según ciudades, 1950-2002*. https://www.memoriachilena.gob.cl/602/w3-article-74944.html

Beguería, S., Vicente Serrano, S. M., Reig-Gracia, F., & Latorre Garcés, B. (2023). *SPEIbase v.2.9 [Dataset]* [Dataset]. DIGITAL.CSIC. https://doi.org/10.20350/digitalCSIC/15470

Belete, M. D., Diekkrüger, B., & Roehrig, J. (2017). Linkage between Water Level Dynamics and Climate Variability: The Case of Lake Hawassa Hydrology and ENSO Phenomena. *Climate*, *5*(1), 21. https://doi.org/10.3390/cli5010021

Bengoa, J. (2000). *Historia del pueblo mapuche: (Siglo XIX y XX)*. Lom Ediciones.

Bengtsson, L. (2012). Water Balance of Lakes. En L. Bengtsson, R. W. Herschy, & R. W. Fairbridge (Eds.), *Encyclopedia of Lakes and Reservoirs* (pp. 863-864). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4410-6_18

Betts, A. K., Reid, D., & Crossett, C. (2020). Evaluation of the FLake Model in ERA5 for Lake Champlain. *Frontiers in Environmental Science*, *8*. https://doi.org/10.3389/fenvs.2020.609254

Beutel, M. W., Horne, A. J., Roth, J. C., & Barratt, N. J. (2001). Limnological effects of anthropogenic desiccation of a large, saline lake, Walker Lake, Nevada. *Hydrobiologia*, *466*(1), 91-105. https://doi.org/10.1023/A:1014569521381

Biblioteca del Congreso Nacional. (2021, octubre 13). *Biblioteca del Congreso Nacional | Ley Chile*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Biblioteca del Congreso Nacional. (2023, septiembre 6). *Ley 21600 CREA EL SERVICIO DE BIODIVERSIDAD Y ÁREAS PROTEGIDAS Y EL SISTEMA*

NACIONAL DE ÁREAS PROTEGIDAS. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Bio Bio (Director). (2023, febrero 13). *Dichos de Boric por regulación de industria forestal fueron catalogados como «fuera de contexto»* [Video recording]. https://www.youtube.com/watch?v=do0zHOXR5Us

Bolados, P., Espinoza, L., & Panez, A. (2024). Una aproximación decolonial a las Zonas de Sacrificio en Chile. *Vibrant: Virtual Brazilian Anthropology*, *21*, e21603. https://www.scielo.br/j/vb/a/vtQ6tPk9TWjThNfhNJTLtcv/?lang=es

Bongioannini Cerlini, P., Saraceni, M., Silvestri, L., Meniconi, S., & Brunone, B. (2022). Monitoring the Water Mass Balance Variability of Small Shallow Lakes by an ERA5-Land Reanalysis and Water Level Measurement-Based Model. An Application to the Trasimeno Lake, Italy. *Atmosphere*, *13*(6), Article 6. https://doi.org/10.3390/atmos13060949

Bonney, P. R., Hansen, B. D., & Baldwin, C. (2023). Citizen Science and Natural Resource Management: A Social Network Analysis of Two Community-Based Water Monitoring Programs. *Society & Natural Resources*, *36*(6), 600-621. https://doi.org/10.1080/08941920.2023.2183445

Boy, F., Crétaux, J.-F., Boussaroque, M., & Tison, C. (2022). Improving Sentinel-3 SAR Mode Processing Over Lake Using Numerical Simulations. *IEEE Transactions on Geoscience and Remote Sensing*, *60*, 1-18. https://doi.org/10.1109/TGRS.2021.3137034

Bravo Ferretti, C., Sandoval-Díaz, J., Astudillo Pizarro, F., Bravo Ferretti, C., Sandoval-Díaz, J., & Astudillo Pizarro, F. (2022). Narrativas del acorralamiento. Identidad de Lugar en la Bahía de Coronel a partir de la reconversión productiva. *Revista de historia (Concepción)*, *29*(1), 73-105. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-88322022000100073&lng=es&nrm=iso&tlng=en

Bravo Orrego, C. M. (2018). *Caracterización de la precipitación en la Cordillera de Nahuelbuta según la microfísica bajo la cual ocurre* [[PhD Thesis], Universidad de Chile]. https://repositorio.uchile.cl/handle/2250/168171

Brown, C. F., Brumby, S. P., Guzder-Williams, B., Birch, T., Hyde, S. B., Mazzariello, J., Czerwinski, W., Pasquarella, V. J., Haertel, R., Ilyushchenko, S., Schwehr, K., Weisse, M., Stolle, F., Hanson, C., Guinan, O., Moore, R., & Tait, A. M. (2022). Dynamic World, Near real-time global 10 m land use land cover mapping. *Scientific Data*, *9*(1), 251. https://www.nature.com/articles/s41597-022-01307-4

Budds, J. (2013). Water, Power, and the Production of Neoliberalism in Chile, 1973–2005. *Environment and Planning D: Society and Space*, *31*(2), 301-318. https://doi.org/10.1068/d9511

Burić, D., & Penjišević, I. (2023). Southern Hemisphere temperature trend in association with greenhouse gases, El Niño Southern Oscillation, and Antarctic Oscillation. *Időjárás*, *127*(1), 23-42. https://doi.org/10.28974/idojaras.2023.1.2

Burns, N. (2020). *Protocol for Monitoring Trophic Levels of New Zealand Lakes and Reservoirs*.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and

water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, *2*. https://www.frontiersin.org/articles/10.3389/feart.2014.00026

Carlson, R. E. (1977). A trophic state index for lakes. *Limnology and Oceanography*, *22*(2), 361-369. https://doi.org/10.4319/lo.1977.22.2.0361

Carmona, A., & Nahuelhual, L. (2012). Combining land transitions and trajectories in assessing forest cover change. *Applied Geography*, *32*(2), 904-915. https://www.sciencedirect.com/science/article/pii/S0143622811001755

Caro, C. S. M. (2003). *Aproximación a las estrategias de sobrevivencia de las familias de la caleta de Boca Sur Viejo en San Pedro de la Paz; experiencia y estudio de caso* [[PhD Thesis]]. Universidad de Concepción.

Carrasco Henríquez, N., & Mendoza Leal, C. (2021). Restoration as a re-commoning process. Territorial initiative and global conditions in the process of water recovery in the 'Cordillera de Nahuelbuta', Chile. *Ecosystems and People*, *17*(1), 556-573. https://doi.org/10.1080/26395916.2021.1993345

Castillo, S. F. (s. f.). *Ciudad y el derecho al buen vivir: Contribución rural a la reconstrucción de espacios fragmentados Barrio Boca Sur, Concepción, Chile.*

Chazdon, R. L., Falk, D. A., Banin, L. F., Wagner, M., J. Wilson, S., Grabowski, R. C., & Suding, K. N. (2024). The intervention continuum in restoration ecology: Rethinking the active–passive dichotomy. *Restoration Ecology*, *32*(8), e13535. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.13535

Cheng, C., Du, W., Li, J., Bao, A., Ge, W., Wang, S., Ma, D., & Pan, Y. (2023). Spatiotemporal Variations of Glacier Mass Balance in the Tomur Peak Region Based on Multi-Source Altimetry Remote Sensing Data. *Remote Sensing*, *15*(17), 4143. https://doi.org/10.3390/rs15174143

Cheng, C., Xing, Z., Ye, L., Yang, J., & Xie, Z. (2024). Characteristics and Influencing Factors of Landscape Pattern Gradient Transformation of Small-Scale Agroforestry Patches in Mountain Cities. *Sustainability*, *16*(15), 6322. https://doi.org/10.3390/su16156322

Chicco, D., Warrens, M. J., & Jurman, G. (2021). The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Computer Science*, *7*, e623. https://doi.org/10.7717/peerj-cs.623

Chile_ING_ESP.xls. (s. f.). Recuperado 25 de julio de 2025, de https://www.memoriachilena.gob.cl/archivos2/pdfs/MC0018840.PDF

Choongik, C. (2025). Unequal Distribution of Climate Change Impacts across Regions: Towards Climate Justice. *Journal of Distribution Science*, *23*(4), 103-116. https://koreascience.kr/article/JAKO202512250404430.page

Choukrani, H., Lacombe, G., Zwarteveen, M., Kuper, M., Taky, A., & Hammani, A. (2023). Sense-making and shaping of temporary wetlands: A socio-hydrological analysis of dichotomous ontologies of merjas in Morocco. *Journal of Hydrology*, 130434. https://doi.org/10.1016/j.jhydrol.2023.130434

Clark, B., & York, R. (2008). Rifts and Shifts: Getting to the Root of Environmental Crises. *Monthly Review*, *60*(6), 13. http://archive.monthlyreview.org/index.php/mr/article/view/MR-060-06-2008-10_2

Clark, N. E., Eber, L. E., Laurs, R. M., Renneer, J. A., & Saur, J. F. T. (1974). *Heat exchange between ocean and atmosphere in the eastern North Pacific for*

1961-71.
https://repository.library.noaa.gov/view/noaa/11864/noaa_11864_DS1.pdf
Clark, & York. (2005). Carbon metabolism: Global capitalism, climate change, and the biospheric rift. *Theory and Society*, *34*(4), 391-428. https://doi.org/10.1007/s11186-005-1993-4
CNES. (2015). *How altimetry works [online]. Toulouse, Centre national d'études spatiales (CNES)*. https://cnes.fr/en/how-altimetry-works
Comisión Presidencial para la Paz y el Entendimiento. (2025). *Resumen ejecutivo de las recomendaciones al Estado de Chile en materia de tierras y derechos del pueblo Mapuche*. Ministerio Secretaría General de la Presidencia. https://www.comisionpazyentendimiento.gob.cl/wp-content/uploads/2025/05/Resumen-Ejecutivo-Oficial-Cierre-Comision-para-la-Paz-y-el-Entendimiento.pdf
Condom, T., Martínez, R., Pabón, J. D., Costa, F., Pineda, L., Nieto, J. J., López, F., & Villacis, M. (2020). Climatological and Hydrological Observations for the South American Andes: In situ Stations, Satellite, and Reanalysis Data Sets. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.00092
Congalton, R. G., Gu, J., Yadav, K., Thenkabail, P., & Ozdogan, M. (2014). Global Land Cover Mapping: A Review and Uncertainty Analysis. *Remote Sensing*, *6*(12), 12070-12093. https://doi.org/10.3390/rs61212070
COPERNICUS. (2025). *Land Monitoring Service: Temperature and Reflectance*. https://land.copernicus.eu/en/products/temperature-and-reflectance
Corporación Junquillar. (2024). *Protocolo de monitoreo de calidad del agua en la Laguna Junquillar*.
Corporación Junquillar. (2025). *Laguna Junquillar (@lagunajunquillar) • Fotos y videos de Instagram*. https://www.instagram.com/lagunajunquillar/
Correa, M. (2021). La Historia del Despojo; El Origen de la Propiedad Particular en el Territorio. *Santiago, Chile: Ceibo-Pehuén Ediciones*.
Cosgrove, A., & Berkelhammer, M. (2018). Downwind footprint of an urban heat island on air and lake temperatures. *Npj Climate and Atmospheric Science*, *1*(1), 46. https://doi.org/10.1038/s41612-018-0055-3
(CR)2. (2025). *Explorador climático (CR)2* (Available online) [Dataset]. https://explorador.cr2.cl/
Cretaux, J., Kouraev, A., Papa, F., Bergé-Nguyen, M., Cazenave, A., Aladin, N., & Plotnikov, I. (2005). *Water balance of the Big Aral Sea from satellite remote sensing and in situ observations*. *31*.
Crétaux, J.-F., Abarca-del-Río, R., Bergé-Nguyen, M., Arsen, A., Drolon, V., Clos, G., & Maisongrande, P. (2016). Lake Volume Monitoring from Space. *Surveys in Geophysics*, *37*(2), 269-305. https://doi.org/10.1007/s10712-016-9362-6
Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011a). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004
Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011b). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., & Birkett, C. (2006). Lake studies from satellite radar altimetry. *Comptes Rendus Geoscience, La Terre observée depuis l'espace*, *338*(14), 1098-1112. https://doi.org/10.1016/j.crte.2006.08.002

CTOH. (2024, julio 10). *Altimetric Time Series Software (AITiS) [software]*. GitLab. https://gitlab.com/ctoh/altis

Cuomo, C. J. (2011). Climate change, vulnerability, and responsibility. *Hypatia*, *26*(4), 690-714.

Da Silva, J. S., Seyler, F., Calmant, S., Rotunno Filho, O. C., Roux, E., Araújo, A. A. M., & Guyot, J. L. (2012). Water level dynamics of Amazon wetlands at the watershed scale by satellite altimetry. *International Journal of Remote Sensing*, *33*(11), 3323-3353. https://doi.org/10.1080/01431161.2010.531914

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018a). Understanding the abrupt climate change in the mid-1970s from a phase-space transform perspective. *Journal of Applied Meteorology and Climatology*, *57*(11), 2551-2560. https://journals.ametsoc.org/view/journals/apme/57/11/jamc-d-17-0345.1.xml

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018b). *Understanding the Abrupt Climate Change in the Mid-1970s from a Phase-Space Transform Perspective*. https://doi.org/10.1175/JAMC-D-17-0345.1

Davidson, N. C., Fluet-Chouinard, E., & Finlayson, C. M. (2018). Global extent and distribution of wetlands: Trends and issues. *Marine and Freshwater Research*, *69*(4), 620-627. https://www.publish.csiro.au/mf/MF17019

Delgado, F., & Rist. (2016). *Las ciencias desde la perspectiva del diálogo de saberes, la transdisciplinariedad y el diálogo intercientífico*.

Deltares. (2025). *Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments User Manual Hydro-Morphodynamics Version: 4.05.* https://www.google.com/search?q=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&oq=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBBzQxOWowajSoAgCwAgE&sourceid=chrome&ie=UTF-8

DGA. (2025a). *Red hidrométrica en línea DGA.* [Dataset]. https://dga.mop.gob.cl/servicioshidrometeorologicos/Paginas/default.aspx

DGA. (2025b). *Sistema Hidrométrico en Línea | Dirección General de Aguas*. https://dga.mop.gob.cl/sistema-hidrometrico-en-linea/

Di Chiro, G. (2015). A New Spelling Of Sustainability: Engaging Feminist-Environmental Justice Theory And Practice. *Practising Feminist Political Ecologies: Moving Beyond The «Green Economy»*, 211-236. https://doi.org/10.5040/9781350221970.ch-007

Echeverría, C., Bolados, G., Rodriguez, J., Aguayo, M., & Premoli, A. (s. f.). Ecología de Paisajes Forestales. *2014*.

ECMWF. (2020). *ECMWF Confluence Wiki: 3.3. OpenIFS: Surface Model HTESSEL [online]. Reading, European Centre for Medium-Range Weather Forecasts*

(ECMWF). https://confluence.ecmwf.int/display/OIFS/3.3+OpenIFS%3A+Surface+Model+HTESSEL

ECMWF. (2025). *ERA5: Data documentation—Copernicus Knowledge Base—ECMWF Confluence Wiki*. https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation

ECMWF/C3S. (2024a). *Earth Engine Data Catalog: ERA5 Monthly Aggregates [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#bands

ECMWF/C3S. (2024b). *Earth Engine Data Catalog: ERA5-Land Monthly Aggregated [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR

ECOMOD. (2025). *COHERENS modelling system. ECOMOD – Marine Ecosystem Modelling*. https://ecomod.be/projects/COHERENS/

EEDC. (2025a). *USGS Landsat 8 Level 2, Collection 2, Tier 1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

EEDC. (2025b). *WorldClim Climatology V1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/WORLDCLIM_V1_MONTHLY?hl=es-419

EEDCa. (2025). *USGS Landsat 8 Collection 2 Tier 1 and Real-Time data Raw Scenes* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_RT?hl=es-419

EEDCb. (2025). *USGS Landsat 8 Collection 2 Tier 1 TOA Reflectanc* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_TOA?hl=es-419

EEDCc. (2025). *USGS Landsat 8 Level 2, Collection 2, Tier 1* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

Elachi, C., & Van Zyl, J. J. (2006). Introduction to the physics and techniques of remote sensing. John Wiley and Sons. *New Jersey. USA 513p*.

Elachi, C., & Zyl, J. J. van. (2021). *Introduction to the Physics and Techniques of Remote Sensing*. John Wiley & Sons.

EMOL, E. M. (2023, febrero 13). *Monsalve y debate abierto por Boric sobre industria forestal: «Sería irracional que la sociedad no diera una discusión»*. Emol. https://www.emol.com/noticias/Nacional/2023/02/13/1086588/monsalve-industria-forestal.html

EROS. (2022, noviembre 9). *USGS EROS Archive—Landsat Archives—Landsat 8-9 OLI/TIRS Collection 2 Level-2 Science Products | U.S. Geological Survey*. https://www.usgs.gov/centers/eros/science/usgs-eros-archive-landsat-archives-landsat-8-9-olitirs-collection-2-level-2

ESA. (2025a). *ATSR Reprocessing for Climate: Lake Surface Water Temperature & Ice Cover (ARC-Lake)*. https://datashare.ed.ac.uk/handle/10283/88

ESA. (2025b). *Summary of RESETlakes (REmote SEnsing of Tipping points in Lakes)*. ESA Climate Office. https://climate.esa.int/en/tipping-points-research/about-resetlakes/about-resetlakes/

European Environment Agency. (2018, julio 3). *Quality element status*. https://www.eea.europa.eu/en/analysis/maps-and-charts/quality-elements-of-water-bodies-water-assessments

Falkenmark, M., & Rockström, J. (2004). *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. Earthscan.

Falvey, M., & Garreaud, R. D. (2009). Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). *Journal of Geophysical Research: Atmospheres*, *114*(D4). https://doi.org/10.1029/2008JD010519

Fang, G. H., Yang, J., Chen, Y. N., & Zammit, C. (2015). Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, *19*(6), 2547-2559. https://doi.org/10.5194/hess-19-2547-2015

Fang, X., & An, D. (2022). Evaluation on sea surface wind speed product of Fengyun-3D satellite microwave radiation imager using ERA-5 dataset. *International Journal of Remote Sensing*, *43*(10), 3671-3691. https://doi.org/10.1080/01431161.2022.2099770

Fang, X., & Stefan, H. G. (1996). Dynamics of heat exchange between sediment and water in a lake. *Water Resources Research*, *32*(6), 1719-1727. https://doi.org/10.1029/96WR00274

FAO. (2025). *NEW! Check out the Open Foris interactive story*. OpenForis. https://www.fao.org/in-action/openforis/en

Farnaz Nojavan, F. N., Kreakie, B. J., Hollister, J. W., & Qian, S. S. (2019). Rethinking the lake trophic state index. *PeerJ*, *7*, e7936. https://doi.org/10.7717/peerj.7936

Fatichi, S. (2025, agosto 1). *Mann-Kendall Test (https://www.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test), MATLAB Central File Exchange. Recuperado 1 agosto, 2025.* https://la.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test

Fernández, I. C., Manuel-Navarrete, D., & Torres-Salinas, R. (2016). Breaking resilient patterns of inequality in Santiago de Chile: Challenges to navigate towards a more sustainable city. *Sustainability*, *8*(8), 820. https://www.mdpi.com/2071-1050/8/8/820

Fernández-Manjarrés, J. F., Roturier, S., & Bilhaut, A.-G. (2018). The emergence of the social-ecological restoration concept. *Restoration Ecology*, *26*(3), 404-410. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.12685

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302-4315. https://doi.org/10.1002/joc.5086

Fischer, R., Tamayo Cordero, F., Ojeda Luna, T., Ferrer Velasco, R., DeDecker, M., Torres, B., Giessen, L., & Günter, S. (2021). Interplay of governance elements and their effects on deforestation in tropical landscapes: Quantitative insights from Ecuador. *World Development*, *148*, 105665. https://www.sciencedirect.com/science/article/pii/S0305750X21002801

Fitchett, L. L., Sorice, M. G., Cobourn, K. M., Boyle, K. J., Klug, J. L., & Weathers, K. C. (2020). Pathways to enhanced lake integrity: A Framework to assess the effectiveness of local lake associations. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *25*(2), 258-268. https://doi.org/10.1111/lre.12308

Flavelle, A. (2003). *Mapping Our Land: Community Mapping Handbook*. Lone Pine.

Fluet-Chouinard, E., Stocker, B. D., Zhang, Z., Malhotra, A., Melton, J. R., Poulter, B., Kaplan, J. O., Goldewijk, K. K., Siebert, S., Minayeva, T., Hugelius, G., Joosten, H., Barthelmes, A., Prigent, C., Aires, F., Hoyt, A. M., Davidson, N., Finlayson, C. M., Lehner, B., … McIntyre, P. B. (2023). Extensive global wetland loss over the past three centuries. *Nature*, *614*(7947), 281-286. https://www.nature.com/articles/s41586-022-05572-6

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R., Chapin, F. S., Seto, K. C., Weber, E. U., Crona, B. I., Daily, G. C., Dasgupta, P., Gaffney, O., Gordon, L. J., Hoff, H., Levin, S. A., … Walker, B. H. (2021). Our future in the Anthropocene biosphere. *Ambio*, *50*(4), 834-869. https://doi.org/10.1007/s13280-021-01544-8

Foster, J. B. (2022). *Capitalism in the Anthropocene: Ecological Ruin or Ecological Revolution*. NYU Press.

Foster, J. B., Clark, B., & York, R. (2011). *The Ecological Rift: Capitalism's War on the Earth*. NYU Press.

Frappart, F., Blarel, F., Fayad, I., Bergé-Nguyen, M., Crétaux, J.-F., Shu, S., Schregenberger, J., & Baghdadi, N. (2021). Evaluation of the Performances of Radar and Lidar Altimetry Missions for Water Level Retrievals in Mountainous Environment: The Case of the Swiss Lakes. *Remote Sensing*, *13*(11), 2196. https://doi.org/10.3390/rs13112196

Frassl, M. A., Boehrer, B., Holtermann, P. L., Hu, W., Klingbeil, K., Peng, Z., Zhu, J., & Rinke, K. (2018). Opportunities and Limits of Using Meteorological Reanalysis Data for Simulating Seasonal to Sub-Daily Water Temperature Dynamics in a Large Shallow Lake. *Water*, *10*(5), Article 5. https://doi.org/10.3390/w10050594

Freshwater Health Index. (2025). Freshwater Health Index. https://www.freshwaterhealthindex.org

Fuentes, I., Fuster, R., Avilés, D., & Vervoort, W. (2021). Water scarcity in central Chile: The effect of climate and land cover changes on hydrologic resources. *Hydrological Sciences Journal*, *66*(6), 1028-1044. https://doi.org/10.1080/02626667.2021.1903475

Fuentes-Hernández, P., Barría-Catalán, T., & Flores-Chávez, J. (2024). Estado, ferrocarril y territorio: Las estrategias gubernamentales para la ocupación de La Araucanía a fines del siglo XIX. *Revista Austral de Ciencias Sociales*, (46), Article 46. http://revistas.uach.cl/index.php/racs/article/view/7557

Fuenzalida, H. (1982). A country of extreme climate. *Chile: Essence and Evolution*, 27-35.

Fundación Terram. (2021). *MINUTA RELATIVA A LA MORTALIDAD MASIVA DE SALMONES CAUSADAS POR FLORACIONES ALGALES NOCIVAS (FAN) EN LAS REGIONES DE LOS LAGOS Y AYSÉN*. https://www.terram.cl/descargar/recursos_naturales/salmonicultura/Minuta-Mortalidad-Masiva-de-Salmones-en-Los-Lagos-y-AyseCC81n.pdf

Fustos-Toribio, I., Manque-Roa, N., Vásquez Antipan, D., Hermosilla Sotomayor, M., & Letelier Gonzalez, V. (2022). Rainfall-induced landslide early warning system based on corrected mesoscale numerical models: An application for the southern Andes. *Natural Hazards and Earth System Sciences*, *22*(6), 2169-2183. https://doi.org/10.5194/nhess-22-2169-2022

Galarce, L. C. (2020, julio 3). Protección de los ecosistemas acuáticos ante la presión de la crisis económica que viene. *CIPER Chile*. https://www.ciperchile.cl/2020/07/03/proteccion-de-los-ecosistemas-acuaticos-ante-la-presion-de-la-crisis-economica-que-viene/

Gao, H., Birkett, C., & Lettenmaier, D. P. (2012). Global monitoring of large reservoir storage from satellite remote sensing. *Water Resources Research*, *48*(9). https://doi.org/10.1029/2012WR012063

Gao, Y., Xie, Y., & Zou, D. (2020). Hydrological regime change and its ecological responses in East Dongting Lake, China. *Ecohydrology & Hydrobiology*, *20*(1), 142-150. https://doi.org/10.1016/j.ecohyd.2019.07.003

Garreaud, R. D. (2009). The Andes climate and weather. *Advances in Geosciences*, *22*, 3-11. https://doi.org/10.5194/adgeo-22-3-2009

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., & Veloso-Aguila, D. (2020). The Central Chile Mega Drought (2010–2018): A climate dynamics perspective. *International Journal of Climatology*, *40*(1), 421-439. https://doi.org/10.1002/joc.6219

Garreaud, R. D., Vuille, M., Compagnucci, R., & Marengo, J. (2009). Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology, Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives*, *281*(3), 180-195. https://doi.org/10.1016/j.palaeo.2007.10.032

Gell, P. A., Finlayson, C. M., & Davidson, N. C. (2023). 1—An introduction to the Ramsar Convention on Wetlands. En P. A. Gell, N. C. Davidson, & C. M. Finlayson (Eds.), *Ramsar Wetlands* (pp. 1-36). Elsevier. https://doi.org/10.1016/B978-0-12-817803-4.00018-8

Gerding, V. (2010). *Suelos de humedales y trumaos húmedos del sur de Chile*. http://biblioteca.cehum.org/handle/CEHUM2018/1628

Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. *Sensors*, *16*(8), 1298. https://doi.org/10.3390/s16081298

Gozingan, A. S., Sohou, Z., Baetens, K., Bonou, F., Baloïtcha, E., Gourgue, O., Romanelli, H., Capet, A., & Lacroix, G. (2024). A 3D numerical baroclinic application of the COHERENS model in the Gulf of Guinea, West Africa. *Regional Studies in Marine Science*, *79*, 103811. https://doi.org/10.1016/j.rsma.2024.103811

Granata, F., & Di Nunno, F. (2025). Pathways for Hydrological Resilience: Strategies for Adaptation in a Changing Climate. *Earth Systems and Environment*. https://doi.org/10.1007/s41748-024-00567-x

Gubrium, J. F., Holstein, J. A., Marvasti, A. B., & McKinney, K. D. (2012). *The SAGE Handbook of Interview Research: The Complexity of the Craft*. SAGE Publications.

Gudynas, E. (2014). *Cuando los extractivismos reconfiguran democracias y derechos Tensiones y contradicciones bajo el progresismo realmente gobernante*.

Gudynas, E. (2015). *Derechos de la naturaleza: Ética biocéntrica y políticas ambientales*. Editorial Abya-Yala. https://books.google.es/books?hl=es&lr=&id=FONZEAAAQBAJ&oi=fnd&pg=PA5&dq=gudynas+2015+pol%C3%ADticas+ambientales&ots=XWxfwm2CuX&sig=WCdqNCNGMdVkOrztuZc7SztKDPU

Gudynas, E. (2017). Beyond varieties of development: Disputes and alternatives. En *Rising Powers and South-South Cooperation*. Routledge.

Guo, M., Zhuang, Q., Yao, H., Golub, M., Leung, L. R., Pierson, D., & Tan, Z. (2021). Validation and Sensitivity Analysis of a 1-D Lake Model Across Global Lakes. *Journal of Geophysical Research: Atmospheres*, *126*(4), e2020JD033417. https://doi.org/10.1029/2020JD033417

Guo, Y., Ren, Z., Dong, Y., Zhang, P., Wang, C., Ma, Z., & He, X. (2023). Multifunctionality can be promoted by increasing agriculture-dominated heterogeneous landscapes in an agro-forestry interlacing zone in northeast China. *Landscape and Urban Planning*, *238*, 104832. https://doi.org/10.1016/j.landurbplan.2023.104832

Hammer, D. A., & Bastian, R. K. (1989). Wetlands Ecosystems: Natural Water Purifiers? En *Constructed Wetlands for Wastewater Treatment*. CRC Press.

Hansen, G. J. A., Wehrly, K. E., Vitense, K., Walsh, J. R., & Jacobson, P. C. (2022). Quantifying the resilience of coldwater lake habitat to climate and land use change to prioritize watershed conservation. *Ecosphere*, *13*(7), e4172. https://doi.org/10.1002/ecs2.4172

Hansen, G., & Stone, D. (2016). Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, *6*(5), 532-537. https://doi.org/10.1038/nclimate2896

Hargrove, A. (2021). The global water crises: A cross-national analysis of metabolic rift theory. *Journal of Political Ecology*, *28*, 2925. https://doi.org/10.2458/jpe.2925

Haustein, K., Allen, M. R., Forster, P. M., Otto, F. E. L., Mitchell, D. M., Matthews, H. D., & Frame, D. J. (2017). A real-time Global Warming Index. *Scientific Reports*, *7*(1), 15417. https://doi.org/10.1038/s41598-017-14828-5

He, C., Malcolm, S. B., Dahlberg, K. A., & Fu, B. (2000). A conceptual framework for integrating hydrological and biological indicators into watershed management. *Landscape and Urban Planning*, *49*(1), 25-34. https://doi.org/10.1016/S0169-2046(00)00047-5

Heilmayr, R., Echeverría, C., Fuentes, R., & Lambin, E. F. (2016). A plantation-dominated forest transition in Chile. *Applied Geography*, *75*, 71-82. https://www.sciencedirect.com/science/article/pii/S0143622816302600

Hernandez, D., Mendoza, P. A., Boisier, J. P., & Ricchetti, F. (2022). Hydrologic Sensitivities and ENSO Variability Across Hydrological Regimes in Central Chile (28°–41°S). *Water Resources Research*, *58*(9), e2021WR031860. https://doi.org/10.1029/2021WR031860

Herod, A. (1993). Gender Issues in the Use of Interviewing as a Research Method∗. *The Professional Geographer*, *45*(3), 305-317. https://doi.org/10.1111/j.0033-0124.1993.00305.x

Hersbach. (2023). *ERA5 hourly data on single levels from 1940 to present*. https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview

Hipsey, M. R., Bruce, L. C., Boon, C., Busch, B., Carey, C. C., Hamilton, D. P., Hanson, P. C., Read, J. S., de Sousa, E., Weber, M., & Winslow, L. A. (2019). A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geoscientific Model Development*, *12*(1), 473-523. https://doi.org/10.5194/gmd-12-473-2019

Hodges, B. R., Imberger, J., & Laval, B. (2000). *Modeling the Hydrodynamics of Stratified Lakes*.

Holling, C. S. (1986). The resilience of terrestrial ecosystems: Local surprise and global change. *Sustainable development of the biosphere*, *14*, 292-317.

Hosseini-Sadabadi, S. A., Rousseau, A. N., Sadeghian, A., Foulon, E., & Behmel, S. (2023). A 3D numerical modeling of the links between hydrodynamics, dissolved oxygen, and water temperature of a northern rural-urban shallow lake with two distinct basins. *Environmental Monitoring and Assessment*, *195*(10), 1198. https://doi.org/10.1007/s10661-023-11744-2

Hou, M., Wei, J., Chu, H., Shi, Y., Ayantobo, O. O., Xu, J., Zhu, X., & Ren, Y. (2022). Conceptual hydrological model-guided SVR approach for monthly lake level reconstruction in the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *44*, 101271. https://doi.org/10.1016/j.ejrh.2022.101271

Hu, S., Niu, Z., & Chen, Y. (2017). Global Wetland Datasets: A Review. *Wetlands*, *37*(5), 807-817. https://doi.org/10.1007/s13157-017-0927-z

Hu, S., Niu, Z., Chen, Y., Li, L., & Zhang, H. (2017). Global wetlands: Potential distribution, wetland loss, and status. *Science of The Total Environment*, *586*, 319-327. https://www.sciencedirect.com/science/article/pii/S0048969717302425

Huang, J., Yu, H., Han, D., Zhang, G., Wei, Y., Huang, J., An, L., Liu, X., & Ren, Y. (2020). Declines in global ecological security under climate change. *Ecological Indicators*, *117*, 106651. https://www.sciencedirect.com/science/article/pii/S1470160X20305884

Huang, L., Wang, J., & Chen, X. (2022). Ecological infrastructure planning of large river basin to promote nature conservation and ecosystem functions. *Journal of Environmental Management*, *306*, 114482. https://www.sciencedirect.com/science/article/pii/S030147972200055X

Huang, L., Woolway, R. I., Timmermann, A., Lee, S.-S., Rodgers, K. B., & Yamaguchi, R. (2024). Emergence of lake conditions that exceed natural temperature variability. *Nature Geoscience*, *17*(8), 763-769. https://doi.org/10.1038/s41561-024-01491-5

Huenupil-Marihuen., M., Garces-Vargas, M., Llevilao-Colil, O., L., A.-P., & Medina-Riquelme, F. (2010). *Historia de Tirúa*.

Huttula, T., & Liukko, N. (2014). *Lake Pyykösjärvi water quality model*.

IDE. (2025). *Infraestructura de datos espaciales. Geoportal de Chile*. https://www.geoportal.cl/catalog

IDE minagri. (2025). *Planificación Catastral | IDE minagri*. https://ide.minagri.gob.cl/geoweb/2019/11/22/planificacion-catastral/

Imberger, J., & Patterson, J. C. (1989). Physical Limnology. En J. W. Hutchinson & T. Y. Wu (Eds.), *Advances in Applied Mechanics* (Vol. 27, pp. 303-475). Elsevier. https://doi.org/10.1016/S0065-2156(08)70199-6

INEa. (2017). *ArcGIS Web Application*. https://ine-chile.maps.arcgis.com/apps/webappviewer/index.html?id=d0bff7af90384faa98d6ff69faa0d6d2

INEb. (2024). *Censo de Población y Vivienda*. Default. http://www.ine.gob.cl/estadisticas/sociales/censos-de-poblacion-y-vivienda/censo-de-poblacion-y-vivienda

INFOR, I. (2014). *Exportaciones forestales chilenas 2013*. INFOR. https://doi.org/10.52904/20.500.12220/20791

Interferencia. (2023, febrero 14). *Ministro de Economía confirma postergación de debate sobre nueva regulación forestal planteada por Boric*. Interferencia. https://interferencia.cl/articulos/ministro-de-economia-confirma-postergacion-de-debate-sobre-nueva-regulacion-forestal

International Lake Environment Committee, I. L. E. C. (2007). Integrated lake basin management: An introduction. *International Lake Environment Committee Foundation. Kusatsu, Japan*, *26*.

International Lake EnvironmentCommitte, I. L. E. (2005). *Managing lakes and their basins for sustainable use: A report for lake basin managers and stakeholders*. International Lake Environment Committee Foundation. https://cir.nii.ac.jp/crid/1971430859734593319

Ishikawa, M., Gonzalez, W., Golyjeswski, O., Sales, G., Rigotti, J. A., Bleninger, T., Mannich, M., & Lorke, A. (2022). Effects of dimensionality on the performance of hydrodynamic models for stratified lakes and reservoirs. *Geoscientific Model Development*, *15*(5), 2197-2220. https://doi.org/10.5194/gmd-15-2197-2022

Iturra Urzúa, J. M. (2024). *Saqueo al humedal de Quilicura. Construcciones sobre el agua*. https://repositorio.uchile.cl/handle/2250/198083

Jacques Coper, M., & Garreaud Salazar, R. (2015). *Characterization of the 1970s climate shift in South America*. https://doi.org/10.1002/joc.4120

Jansen, J., Simpson, G. L., Weyhenmeyer, G. A., Härkönen, L. H., Paterson, A. M., del Giorgio, P. A., & Prairie, Y. T. (2024). Climate-driven deoxygenation of northern lakes. *Nature Climate Change*, *14*(8), 832-838. https://doi.org/10.1038/s41558-024-02058-3

Jerlov. (1968). *Optical Oceanography*. Elsevier.

Ji, L., Senay, G. B., & Verdin, J. P. (2015). *Evaluation of the Global Land Data Assimilation System (GLDAS) Air Temperature Data Products*. https://doi.org/10.1175/JHM-D-14-0230.1

Jian, J., Ryu, D., Costelloe, J. F., & Su, C.-H. (2017). Towards hydrological model calibration using river level measurements. *Journal of Hydrology: Regional Studies*, *10*, 95-109. https://doi.org/10.1016/j.ejrh.2016.12.085

Jiang, Q., Li, W., Fan, Z., He, X., Sun, W., Chen, S., Wen, J., Gao, J., & Wang, J. (2021). Evaluation of the ERA5 reanalysis precipitation dataset over Chinese Mainland. *Journal of Hydrology*, *595*, 125660. https://doi.org/10.1016/j.jhydrol.2020.125660

Jorgensen, S. E., & Rast, W. (2007). The use of models for synthesizing knowledge for integrated lake basin management, and facilitating implementation of the World Lake Vision. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *12*(1), 3-13. https://doi.org/10.1111/j.1440-1770.2007.00316.x

Kanazawa, M. (2023). *Research Methods for Environmental Studies: A Social Science Approach* (2.ª ed.). Routledge. https://doi.org/10.4324/9781003261117

Kay, J. J., & Schneider, E. (1995). Embracing Complexity the Challenge of the Ecosystem Approach. En L. Westra & J. Lemons (Eds.), *Perspectives on Ecological Integrity* (pp. 49-59). Springer Netherlands. https://doi.org/10.1007/978-94-011-0451-7_4

Kaya, Y. (2025). Evaluation of ICESat-2 Laser Altimetry for Inland Water Level Monitoring: A Case Study of Canadian Lakes. *Water*, *17*(7), 1098. https://doi.org/10.3390/w17071098

Kaya, Y., Balik Sanli, F., & Abdikan, S. (2025). Refinement of ICESat-2 derived inland water surface levels with the TG20 local geoid model: In the case of Türkiye lakes. *Physics and Chemistry of the Earth, Parts A/B/C*, *139*, 103900. https://doi.org/10.1016/j.pce.2025.103900

King, A. W. (1993). Considerations of Scale and Hierarchy. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Kirby, R. R., Beaugrand, G., Kleparski, L., Goodall, S., & Lavender, S. (2021). Citizens and scientists collect comparable oceanographic data: Measurements of ocean transparency from the Secchi Disk study and science programmes. *Scientific Reports*, *11*(1), 15499. https://doi.org/10.1038/s41598-021-95029-z

KNMI. (2024). *KNMI Climate explorer*. https://climexp.knmi.nl/selectindex.cgi?id=someone@somewhere

Kondo, J. (1975). Air-sea bulk transfer coefficients in diabatic conditions. *Boundary-Layer Meteorology*, *9*(1), 91-112. https://doi.org/10.1007/BF00232256

Korkou, M., Tarigan, A. K. M., & Hanslin, H. M. (2023). The multifunctionality concept in urban green infrastructure planning: A systematic literature review. *Urban Forestry & Urban Greening*, *85*, 127975. https://doi.org/10.1016/j.ufug.2023.127975

Kornijów, R. (2023). Lake aging concept revisited: Alternative comprehensive approach to lake ontogeny. *Canadian Journal of Fisheries and Aquatic Sciences*, *80*(8), 1385-1393. https://doi.org/10.1139/cjfas-2023-0027

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259-263. https://doi.org/10.1127/0941-2948/2006/0130

Kreakie, B. J., Shivers, S. D., Hollister, J. W., & Milstead, W. B. (2021). Predictive Model of Lake Photic Zone Temperature Across the Conterminous United States. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.707874

Kumar, L., & Mutanga, O. (2018). Google Earth Engine Applications Since Inception: Usage, Trends, and Potential. *Remote Sensing*, *10*(10), Article 10. https://doi.org/10.3390/rs10101509

Kwak, T. J., & Freeman, M. (2010). *Assessment and management of ecological integrity: Chapter 12*. 353-394. https://pubs.usgs.gov/publication/70154946

Labraña-Muñoz, C., & Arcas-Morales, G. (2006). San Pedro de la Paz: Del Fuerte a la comuna (1604-2001). *Hualpén, Chile: Impresos Andalién, Ilustre Municipalidad de San Pedro de la Paz*.

Lara, A., Jones, J., Little, C., & Vergara, N. (2021). Streamflow response to native forest restoration in former Eucalyptus plantations in south central Chile. *Hydrological Processes*, *35*(8), e14270. https://doi.org/10.1002/hyp.14270

Lara, A., Solari, M. E., Prieto, M. D. R., & Peña, M. P. (2012). Reconstrucción de la cobertura de la vegetación y uso del suelo hacia 1550 y sus cambios a 2007 en la ecorregión de los bosques valdivianos lluviosos de Chile (35º—43º 30´ S). *Bosque (Valdivia)*, *33*(1), 13-23. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-92002012000100002&lng=es&nrm=iso&tlng=en

Lee, J.-W., Park, S.-R., & Lee, S.-W. (2023). Effect of Land Use on Stream Water Quality and Biological Conditions in Multi-Scale Watersheds. *Water*, *15*(24), 4210. https://doi.org/10.3390/w15244210

Lee, K., Nam, S., Cho, Y.-K., Jeong, K.-Y., & Byun, D.-S. (2022). Determination of Long-Term (1993–2019) Sea Level Rise Trends Around the Korean Peninsula Using Ocean Tide-Corrected, Multi-Mission Satellite Altimetry Data. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.810549

Lewis, S. L., & Maslin, M. A. (2015). Defining the Anthropocene. *Nature*, *519*(7542), 171-180. https://www.nature.com/articles/nature14258

Lieberherr, G., & Wunderle, S. (2018). Lake Surface Water Temperature Derived from 35 Years of AVHRR Sensor Data for European Lakes. *Remote Sensing*, *10*(7), Article 7. https://doi.org/10.3390/rs10070990

Lin, S., Boegman, L., Shan, S., & Mulligan, R. (2022). An automatic lake-model application using near-real-time data forcing: Development of an operational forecast workflow (COASTLINES) for Lake Erie. *Geoscientific Model Development*, *15*(3), 1331-1353. https://doi.org/10.5194/gmd-15-1331-2022

Little, C., Lara, A., McPhee, J., & Urrutia, R. (2009). Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile. *Journal of Hydrology*, *374*(1), 162-170. https://doi.org/10.1016/j.jhydrol.2009.06.011

Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., Valenzuela, R. A., Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., & Valenzuela, R. A. (2017). La agricultura y la élite agraria chilena a través de los catastros agrícolas, c. 1830-1855. *Historia (Santiago)*, *50*(2), 597-639. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-71942017000200597&lng=es&nrm=iso&tlng=es

Long, L. (2017, marzo 1). The Stages of Lake and Pond Succession. *SOLitude Lake Management: Full-Service Lake And Pond Management*. https://www.solitudelakemanagement.com/the-stages-of-lake-and-pond-succession/

Lovell, S. T. (2010). Multifunctional Urban Agriculture for Sustainable Land Use Planning in the United States. *Sustainability*, *2*(8), 2499-2522. https://doi.org/10.3390/su2082499

Luo, J., Duan, H., Xu, Y., Shen, M., Zhang, Y., Xiao, Q., Ni, G., Wang, K., Xin, Y., Qi, T., Feng, L., Qiu, Y., Jeppesen, E., & Woolway, R. I. (2025). Global trends and regime state shifts of lacustrine aquatic vegetation. *The Innovation*, *6*(3), 100784. https://doi.org/10.1016/j.xinn.2024.100784

Luyten, P. (2025). *COHERENS: A Coupled Hydrodynamical Ecological Model for Regional and Shelf Seas: User Documentation (Version 3)*. Operational Directorate Natural Environment, Royal Belgian Institute of Natural Sciences. https://doi.org/10.5281/zenodo.11261106.

Lyche Solheim, A., Globevnik, L., Austnes, K., Kristensen, P., Moe, S. J., Persson, J., Phillips, G., Poikane, S., van de Bund, W., & Birk, S. (2019). A new broad typology for rivers and lakes in Europe: Development and application for large-scale environmental assessments. *Science of The Total Environment*, *697*, 134043. https://doi.org/10.1016/j.scitotenv.2019.134043

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J. B., Jena, J., Bhattacharya, U., Duvvada, S. K., Lalichetti, S., & Sairam, M. (2021). Intercropping—A Low Input

Agricultural Strategy for Food and Environmental Security. *Agronomy*, *11*(2), Article 2. https://www.mdpi.com/2073-4395/11/2/343

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015a). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*, 331-340. https://doi.org/10.1016/j.agwat.2015.06.022

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015b). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*(C), 331-340. https://ideas.repec.org//a/eee/agiwat/v159y2015icp331-340.html

Mano, A., Malve, O., Koponen, S., Kallio, K., Taskinen, A., Ropponen, J., Juntunen, J., & Liukko, N. (2015). Assimilation of satellite data to 3D hydrodynamic model of Lake Säkylän Pyhäjärvi. *Water Science and Technology*, *71*(7), 1033-1039. https://doi.org/10.2166/wst.2015.042

Mano, A., & Shuku, T. (2014). *Application of the Particle Filter to COHERENS V2 model of Lake Säkylän Pyhäjärvi*.

Manuschevich, D. (2016). Neoliberalization of forestry discourses in Chile. *Forest Policy and Economics*, *69*, 21-30. https://doi.org/10.1016/j.forpol.2016.03.006

Marinov, D., Norro, A., & Zaldívar, J.-M. (2006). Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore). *Ecological Modelling, Special Issue on Southern European Coastal Lagoons*, *193*(1), 52-68. https://doi.org/10.1016/j.ecolmodel.2005.07.042

Martínez Retureta, R. (2021). *Efectos del cambio de uso cobertura del suelo sobre la respuesta hidrológica en cuencas del centro sur de Chile bajo escenarios de cambio climático.* https://repositorio.udec.cl/handle/11594/6538

Martínez-Fernández, J., Banos-González, I., & Esteve-Selma, M. Á. (2021). An integral approach to address socio-ecological systems sustainability and their uncertainties. *Science of The Total Environment*, *762*, 144457. https://www.sciencedirect.com/science/article/pii/S0048969720379882

Martínez-Tilleria, K., Núñez-Ávila, M., León, C. A., Pliscoff, P., Squeo, F. A., & Armesto, J. J. (2017). A framework for the classification Chilean terrestrial ecosystems as a tool for achieving global conservation targets. *Biodiversity and Conservation*, *26*(12), 2857-2876. https://doi.org/10.1007/s10531-017-1393-x

Marttunen, M., Hellsten, S., Glover, B., Tarvainen, A., Klintwall, L., Olsson, H., & Pedersen, T. S. (2006). Heavily regulated lakes and the European Water framework directive—Comparisons from Finland, Norway, Sweden, Scotland and Austria. *E-Water*, *5*, 1-22. https://www.ewa-online.eu/files/downloads/publications/E-Water_Journal/42_2006_05.pdf

Mason, I. M., Guzkowska, M. A. J., Rapley, C. G., & Street-Perrott, F. A. (1994). The response of lake levels and areas to climatic change. *Climatic Change*, *27*(2), 161-197. https://doi.org/10.1007/BF01093590

Mayer, A. L., & Rietkerk, M. (2004). The Dynamic Regime Concept for Ecosystem Management and Restoration. *BioScience*, *54*(11), 1013-1020. https://doi.org/10.1641/0006-3568(2004)054[1013:TDRCFE]2.0.CO;2

McDougall, T. J., Jackett, D. R., Wright, D. G., & Feistel, R. (2003). *Accurate and Computationally Efficient Algorithms for Potential Temperature and Density of*

Seawater. https://journals.ametsoc.org/view/journals/atot/20/5/1520-0426_2003_20_730_aaceaf_2_0_co_2.xml

McGregor, G. (2017). Hydroclimatology, modes of climatic variability and stream flow, lake and groundwater level variability: A progress report. *Progress in Physical Geography: Earth and Environment*, *41*(4), 496-512. https://doi.org/10.1177/0309133317726537

Meerhoff, M., Audet, J., Davidson, T. A., De Meester, L., Hilt, S., Kosten, S., Liu, Z., Mazzeo, N., Paerl, H., Scheffer, M., & Jeppesen, E. (2022). Feedback between climate change and eutrophication: Revisiting the allied attack concept and how to strike back. *Inland Waters*, *12*(2), 187-204. https://doi.org/10.1080/20442041.2022.2029317

Mellor, G. L. (1988). *A THREE-DIMENSIONAL, PRIMITIVE EQUATION, NUMERICAL OCEAN MODEL*.

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016a). Trophic State Index estimation from remote sensing of lake Chapala, México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016b). Trophic State Index estimation from remote sensing of lake Chapala, México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Meng, B., Liu, J., Bao, K., & Sun, B. (2020). Methodologies and Management Framework for Restoration of Wetland Hydrologic Connectivity: A Synthesis. *Integrated Environmental Assessment and Management*, *16*(4), 438-451. https://doi.org/10.1002/ieam.4256

Merryfield, W. J., & Lee, W.-S. (2023). Estimating Probabilities of Extreme ENSO Events from Copernicus Seasonal Hindcasts. *Asia-Pacific Journal of Atmospheric Sciences*, *59*(4), 479-493. https://doi.org/10.1007/s13143-023-00328-2

Metcalfe, A. N., Kennedy, T. A., Mendez, G. A., & Muehlbauer, J. D. (2022). Applied citizen science in freshwater research. *WIREs Water*, *9*(2), e1578. https://doi.org/10.1002/wat2.1578

Mironov, D., Golosov, S., Heise, E., Kourzeneva, E., Ritter, B., Schneider, N., & Terzhevik, A. (2005). FLake – A Lake Model for Environmental Applications. *2005*.

Mitra, S., Wassmann, R., & Vlek, P. L. G. (2003). *Global inventory of wetlands and their role in the carbon cycle* (ZEF - Discussion Papers on Development Policy No. 64). https://doi.org/10.22004/ag.econ.18771

MMA. (2020). *ANTEPROYECTO DEL PLAN DE DESCONTAMINACION POR CLOROFILA "A", TliANSPARENCIA Y FOSFORO DISUELTO, PARA LA CUENCA DEL LAGO VILLARRICA.* https://consultaindigena.mma.gob.cl/wp-content/uploads/2021/11/Anteproyecto-PDA-Lago-Villarrica.pdf

Montecinos, A., & Aceituno, P. (2003). *Seasonality of the ENSO-Related Rainfall Variability in Central Chile and Associated Circulation Anomalies*. https://journals.ametsoc.org/view/journals/clim/16/2/1520-0442_2003_016_0281_soterr_2.0.co_2.xml

Morales-Magaña, M., Paneque-Galvez, J., Torres-Abreu, A., Mori-González, R., Reyes Díaz, A. M., Rivera Ramos, J. C., Molina Carrasquillo, R., & Molina Parrilla, S. C. (2020). *Community experiences in water management: Social innovation, participatory science, and dialogue of knowledges II (in Portuguese and Spanish)*. https://doi.org/10.5281/zenodo.4362629

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, *50*(3), 885-900. https://doi.org/10.13031/2013.23153

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). *Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria*.

Mortimer, C. H. (1974). Lake hydrodynamics. *Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Mitteilungen*. (world). https://www.tandfonline.com/doi/abs/10.1080/05384680.1974.11923886

Mukaka, M. M. (2012). A guide to appropriate use of Correlation coefficient in medical research. *Malawi Medical Journal*, *24*(3), 69-71. https://www.ajol.info/index.php/mmj/article/view/81576

Muñoz Aguayo, P. (2013). *Apuntes de teledetección: Índices de vegetación.* https://bibliotecadigital.ciren.cl/bitstreams/af8fd625-0d58-4941-8530-7186a6b3d93e/download

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349-4383. https://doi.org/10.5194/essd-13-4349-2021

Naciones Unidas, M. J. (2025). Objetivos y metas de desarrollo sostenible. *Desarrollo Sostenible*. https://www.un.org/sustainabledevelopment/es/objetivos-de-desarrollo-sostenible/

NASA. (2025). *ASF Data Search*. https://search.asf.alaska.edu/

NASA SWOT. (2024). *NASA SWOT. Jet Propulsion Laboratory: Surface Water and Ocean Topography (SWOT).* https://swot.jpl.nasa.gov/

National Institute of Water and Atmospheric Research. (2025). *Lakespi (Lake Submerged Plant Indicators)*. https://lakespi.niwa.co.nz/

Ndehedehe, C. E., Awange, J. L., Kuhn, M., Agutu, N. O., & Fukuda, Y. (2017). Analysis of hydrological variability over the Volta river basin using in-situ data and satellite observations. *Journal of Hydrology: Regional Studies*, *12*, 88-110. https://doi.org/10.1016/j.ejrh.2017.04.005

Nekouee, N., Hamidi, S. A., Roberts, P. J. W., & Schwab, D. J. (2015). Assessment of a 3D Hydrostatic Model (POM) in the Near Field of a Buoyant River Plume in Lake Michigan. *Water, Air, & Soil Pollution*, *226*(7), 210. https://doi.org/10.1007/s11270-015-2488-1

Ngamile, S., Madonsela, S., & Kganyago, M. (2025). Trends in remote sensing of water quality parameters in inland water bodies: A systematic review. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1549301

Nhamo, L., Magidi, J., & Dickens, C. (2017). Determining wetland spatial extent and seasonal variations of the inundated area using multispectral remote sensing. *Water SA*, *43*(4), 543-552. https://doi.org/10.4314/wsa.v43i4.02

Nielsen, L. (2020, enero). *(PDF) Toward a unified theory of risk, resilience and sustainability science with applications for education and governance*. https://www.researchgate.net/publication/348407042_Toward_a_unified_theory_of_risk_resilience_and_sustainability_science_with_applications_for_education_and_governance

NOAA. (2024a). *El Niño / Southern Oscillation (ENSO) | Equatorial Pacific Sea Surface Temperatures (SST) | National Centers for Environmental Information (NCEI)*. https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024b). *National Oceanic and Atmospheric Administration (NOAA). Antartic Oscillation.* https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml

NOAA. (2024c). *National Oceanic and Atmospheric Administration (NOAA). Equatorial Pacific Sea Surface Temperatures (SST).* https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024d). *National Oceanic and Atmospheric Administration (NOAA). Pacific Decadal Oscillation (PDO).* https://www.ncei.noaa.gov/access/monitoring/pdo/

Odeku, K. O. (2022). Climate injustices due to the unequal and disproportionate impacts of climate change. *Perspectives of Law and Public Administration*, *11*(1), 103-110. https://www.ceeol.com/search/article-detail?id=1102605

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., & Calvez, R. (2018). Surface water monitoring in small water bodies: Potential and limits of multi-sensor Landsat time series. *Hydrology and Earth System Sciences*, *22*(8), 4349-4380. https://doi.org/10.5194/hess-22-4349-2018

Olvera, M. J. T. (2018). *Integridad ecológica como una herramienta de evaluación en cuencas hidrográficas. Caso de estudio Microcuenca del Río Jalpan*. https://ring.uaq.mx/handle/123456789/1004

Onyutha, C. (2021). A hydrological model skill score and revised R-squared. *Hydrology Research*, *53*(1), 51-64. https://doi.org/10.2166/nh.2021.071

Oppliger, A. (2015). *Atlas del Agua – Chile 2016 / Atlas of Water—Chile 2016*. Ministry of Public Works - General Direction of Waters of Chile. https://iris.unil.ch/handle/iris/49995

O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J. D., McIntyre, P. B., Kraemer, B. M., Weyhenmeyer, G. A., Straile, D., Dong, B., Adrian, R., Allan, M. G., Anneville, O., Arvola, L., Austin, J., Bailey, J. L., … Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, *42*(24), 10,773-10,781. https://doi.org/10.1002/2015GL066235

Organización del Tratado de Cooperación Amazónica. (2025). *Proyecto Cuenca Amazónica. Implementación del Programa de Acciones Estratégicas en la Cuenca del río Amazonas considerando la Variabilidad y el Cambio Climático.* https://aguasamazonicas.otca.org/monitoreo-ambiental-y-de-los-recursos-hidricos/sistema-integrado-de-monitoreo-de-los-recursos-hidricos/

Ortiz, A. M. D., Gayó, E. M., Henríquez, N. C., Henríquez, B. J., & Pauchard, A. (2024). Exploring the multifunctional landscapes model in areas dominated by

non-native tree plantations. *Trees, Forests and People*, *17*, 100617. https://www.sciencedirect.com/science/article/pii/S2666719324001249

Otavo, S., & Echeverría, C. (2017). Fragmentación progresiva y pérdida de hábitat de bosques naturales en uno de los hotspot mundiales de biodiversidad. *Revista Mexicana de Biodiversidad*, *88*(4), 924-935. https://doi.org/10.1016/j.rmb.2017.10.041

Otero Durán, L. (2012). La huella del fuego: Historia de los bosques nativos poblamiento y cambios en el paisaje de lsur de Chile. *2012*. https://www.sidalc.net/search/Record/KOHA-OAI-FCF:15776/Description

Oxley, R. L. (2015). *Ecological, environmental and hydrological integrity in sustainable water resource management for river basins*. Arizona State University. https://search.proquest.com/openview/4d57cce5b508c9900cd2f564fdc817bd/1?pq-origsite=gscholar&cbl=18750

Palomo, I., Locatelli, B., Otero, I., Colloff, M., Crouzat, E., Cuni-Sanchez, A., Gómez-Baggethun, E., González-García, A., Grêt-Regamey, A., Jiménez-Aceituno, A., Martín-López, B., Pascual, U., Zafra-Calvo, N., Bruley, E., Fischborn, M., Metz, R., & Lavorel, S. (2021). Assessing nature-based solutions for transformative change. *One Earth*, *4*(5), 730-741. https://doi.org/10.1016/j.oneear.2021.04.013

Paredes, M. L., & Ulloa, M. E. (2021). Implementación de los ECMPO y las disputas por el control del territorio: El caso del ECMPO Mañihueico-Huinay y los mitilicultores de la comuna de Hualaihué, Región de Los Lagos. *Revista LIDER*, 62-87. https://revistas.ulagos.cl/index.php/index

Pareeth, S., Salmaso, N., Adrian, R., & Neteler, M. (2016). Homogenised daily lake surface water temperature data generated from multiple satellite sensors: A long-term case study of a large sub-Alpine lake. *Scientific Reports*, *6*(1), 31251. https://doi.org/10.1038/srep31251

Parra et al. (2016). *Una aproximación interdisciplinaria al estudio... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Una+aproximaci%C3%B3n+interdisciplinaria+al+estudio+de+floraciones+de+algas+nocivas+en+Lagos+Urbanos+En+Chile&author=Parra,+O.&author=Baeza,+C.&author=Almanza,+V.&author=Urrutia,+R.&author=Figueroa,+R.&author=Fern%C3%A1ndez,+X.&author=de+Or%C3%BAe,+P.&author=Gonz%C3%A1lez,+P.&author=Beltr%C3%A1n,+J.&author=Becerra,+J.&publication_year=2016&pages=133%E2%80%93146

Parra et al., O. (2003). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*, 51-83. https://ui.adsabs.harvard.edu/abs/2003Limne..22...51P

Parra, O. (2003a). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://doi.org/10.23818/limn.22.04

Parra, O. (2003b). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://www.limnetica.net/documentos/limnetica/limnetica-22-1-p-51.pdf

Parra, O., Basualto, S., Urrutia, R., & Valdovinos, C. (1999). Estudio comparativo de la diversidad fitoplanctónica de cinco lagos de diferentes niveles de eutroficación del área litoral de la región del Biobio (Chile). *Gayana Botánica (Chile)*, *56*, 93-108.

Parra, O. O. (1989). *La eutroficación de la Laguna Grande de San Pedro, Concepción, Chile: Un caso de estudio.*

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005a). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005b). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Pedreros-Guarda, M. (2025). *Github COHERENS Lake*. https://github.com/mpedreros/COHERENS_Lake.git

Pedreros-Guarda, M. (2025). *Mpedreros/TesisDoctoral* [Software]. https://github.com/mpedreros/TesisDoctoral (Obra original publicada en 2025)

Pedreros-Guarda, M., Abarca-del-Río, R., Crétaux, J. F., & Paris, A. (2025). Long-term lake water levels in central Chile using satellite altimetry and conceptual hydrological modelling approaches. *Advances in Space Research*, *76*(4), 1997-2018. https://doi.org/10.1016/j.asr.2025.05.091

Pedreros-Guarda, M., Abarca-del-Río, R., Escalona, K., García, I., & Parra, Ó. (2021). A Google Earth Engine Application to Retrieve Long-Term Surface Temperature for Small Lakes. Case: San Pedro Lagoons, Chile. *Remote Sensing*, *13*(22), 4544. https://doi.org/10.3390/rs13224544

Piccioni, F., Casenave, C., Lemaire, B. J., Le Moigne, P., Dubois, P., & Vinçon-Leite, B. (2021). The thermal response of small and shallow lakes to climate change: New insights from 3D hindcast modelling. *Earth System Dynamics*, *12*(2), 439-456. https://doi.org/10.5194/esd-12-439-2021

Piccolroaz, S., Toffolon, M., & Majone, B. (2013). A simple lumped model to convert air temperature into surface water temperature in lakes. *Hydrology and Earth System Sciences*, *17*(8), 3323-3338. https://doi.org/10.5194/hess-17-3323-2013

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024a). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024b). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Pilla, R. M., Williamson, C. E., Zhang, J., Smyth, R. L., Lenters, J. D., Brentrup, J. A., Knoll, L. B., & Fisher, T. J. (2018). Browning-Related Decreases in Water Transparency Lead to Long-Term Increases in Surface Water Temperature and Thermal Stratification in Two Small Lakes. *Journal of Geophysical Research: Biogeosciences*, *123*(5), 1651-1665. https://doi.org/10.1029/2017JG004321

Pinto, A. P., García, P. B., Almonacid, L. E., & Henríquez, B. J. (2023). Zonas de Sacrificio y Recuperación Socioambiental en Chile: Fallas y oportunidades de la política ambiental. *Ambiente & Sociedade*, *26*, e01371. https://www.scielo.br/j/asoc/a/JdDjvNrLpBJPKwYfppfDBWB/

Prats, J., Reynaud, N., Rebière, D., Peroux, T., Tormos, T., & Danis, P.-A. (2018). LakeSST: Lake Skin Surface Temperature in French inland water bodies for 1999–2016 from Landsat archives. *Earth System Science Data*, *10*(2), 727-743. https://doi.org/10.5194/essd-10-727-2018

Qiao, B., Du, T., Ju, J., & Zhu, L. (2025). Water depth inversion based on ICESat-2 and Sentinel-2—A case study of Qiagui Co and Ayakekumu Lake on the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *59*, 102354. https://doi.org/10.1016/j.ejrh.2025.102354

Quevedo, F., Rojas Hernández, J., & Barra, R. O. (2022). Towards a Chilean Water Governance: A Study on the Los Batros and Paicaví Wetland Reservoirs. *Water*, *14*(18), Article 18. https://www.mdpi.com/2073-4441/14/18/2861

Quintana, J. M., & Aceituno, P. (2012). Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30-43º S. *Atmósfera*, *25*(1), 1-22. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S0187-62362012000100001&lng=es&nrm=iso&tlng=en

Randrianiaina, Rakotonirina, Ratiarimanana, & Lahatra. (2018). *Temperature Retrieval of Lake Itasy Using Remote Sensing*. https://scholar.google.com/scholar_lookup?title=Temperature+Retrieval+of+Lake+Itasy+Using+Remote+Sensing&author=Randrianiaina,+J.&author=Rakotonirina,+I.&author=Ratiarimanana,+R.&author=Lahatra,+F.&publication_year=2018&journal=Resour.+Environ.&volume=8&pages=241%E2%80%93244

Regier, H. A. (1993a). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Regier, H. A. (1993b). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Renting, H., Rossing, W. A. H., Groot, J. C. J., Van der Ploeg, J. D., Laurent, C., Perraud, D., Stobbelaar, D. J., & Van Ittersum, M. K. (2009). Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. *Journal of Environmental Management, Multifunctional agriculture - From farm diagnosis to farm design and institutional innovation*, *90*, S112-S123. https://doi.org/10.1016/j.jenvman.2008.11.014

Restrepo, L. A. V., & Sal, A. G. (2008). Un marco conceptual y analítico para estimar la integridad ecológica a escala de paisaje. *Arbor*, *184*(729), Article 729. https://arbor.revistas.csic.es/index.php/arbor/article/view/159

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Roche, P. K., & Campagne, C. S. (2017). From ecosystem integrity to ecosystem condition: A continuity of concepts supporting different aspects of ecosystem sustainability. *Current Opinion in Environmental Sustainability*, *29*, 63-68. https://www.sciencedirect.com/science/article/pii/S1877343517302828

Rockström, J., Donges, J. F., Fetzer, I., Martin, M. A., Wang-Erlandsson, L., & Richardson, K. (2024). Planetary Boundaries guide humanity's future on

Earth. *Nature Reviews Earth & Environment*, *5*(11), 773-788. https://www.nature.com/articles/s43017-024-00597-z

Rojas Quezada, C. A., Muñiz Olivera, I., & García-López, M. Á. (2009). Estructura urbana y policentrismo en el Área Metropolitana de Concepción. *EURE (Santiago)*, *35*(105), 47-70. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0250-71612009000200003&lng=es&nrm=iso&tlng=es

Rutllant, J., & Fuenzalida, H. (1991). Synoptic aspects of the central chile rainfall variability associated with the southern oscillation. *International Journal of Climatology*, *11*(1), 63-76. https://doi.org/10.1002/joc.3370110105

Salazar, Á., Thatcher, M., Goubanova, K., Bernal, P., Gutiérrez, J., & Squeo, F. (2024). CMIP6 precipitation and temperature projections for Chile. *Climate Dynamics*, *62*(3), 2475-2498. https://doi.org/10.1007/s00382-023-07034-9

Saloranta, T. M., & Andersen, T. (2007). MyLake—A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations. *Ecological Modelling, Uncertainty in Ecological Models*, *207*(1), 45-60. https://doi.org/10.1016/j.ecolmodel.2007.03.018

San Llorente Capdevila, A., Kokimova, A., Sinha Ray, S., Avellán, T., Kim, J., & Kirschke, S. (2020). Success factors for citizen science projects in water quality monitoring. *Science of The Total Environment*, *728*, 137843. https://doi.org/10.1016/j.scitotenv.2020.137843

Saraceni, M., Brunone, B., Silvestri, L., Meniconi, S., & Cerlini, P. B. (2025). *A Water Mass Balance–Based Procedure Using ERA5 Land Reanalysis and Level Observation to Reconstruct the Past Level Changes of Closed Lakes toward Future Management*. https://doi.org/10.1175/JHM-D-24-0019.1

Sarkar, D., Kar, S. K., Chattopadhyay, A., Shikha, Rakshit, A., Tripathi, V. K., Dubey, P. K., & Abhilash, P. C. (2020). Low input sustainable agriculture: A viable climate-smart option for boosting food production in a warming world. *Ecological Indicators*, *115*, 106412. https://www.sciencedirect.com/science/article/pii/S1470160X20303496

Sarkar, S., & Maity, R. (2021). Global climate shift in 1970s causes a significant worldwide increase in precipitation extremes. *Scientific Reports*, *11*(1), 11574. https://doi.org/10.1038/s41598-021-90854-8

Sarricolea, P., Herrera-Ossandon, M., & Meseguer-Ruiz, Ó. (2017). Climatic regionalisation of continental Chile. *Journal of Maps*, *13*(2), 66-73. https://doi.org/10.1080/17445647.2016.1259592

Sazib, N., Mladenova, I., & Bolten, J. (2018). Leveraging the Google Earth Engine for Drought Assessment Using Global Soil Moisture Data. *Remote Sensing*, *10*(8), Article 8. https://doi.org/10.3390/rs10081265

Schallenberg, M., de Winton, M. D., & Kelly, D. J. (2018). Indicators of Ecological Integrity. En D. P. Hamilton, K. J. Collier, J. M. Quinn, & C. Howard-Williams (Eds.), *Lake Restoration Handbook: A New Zealand Perspective* (pp. 367-393). Springer International Publishing. https://doi.org/10.1007/978-3-319-93043-5_11

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591-596. https://doi.org/10.1038/35098000

Schmid, M., & Read, J. (2022). Heat budget of lakes. En *Encyclopedia of inland waters* (Vol. 1, pp. 467-473). https://doi.org/10.1016/b978-0-12-819166-8.00011-6

Schmithuesen, F. (2007). Multifunctional forestry practices as a land use strategy to meet increasing private and public demands in modern societies. *Journal of Forest Science - UZPI (Czech Republic)*, *53*(6). https://agris.fao.org/search/en/providers/122644/records/647247a2e17b74d2224f615d

Schott, F. A., Wang, W., & Stammer, D. (2007). Variability of Pacific subtropical cells in the 50-year ECCO assimilation. *Geophysical Research Letters*, *34*(5). https://doi.org/10.1029/2006GL028478

Schwatke, C., Dettmering, D., Bosch, W., & Seitz, F. (2015). DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrology and Earth System Sciences*, *19*(10), 4345-4364. https://doi.org/10.5194/hess-19-4345-2015

Seidl, R., & Barthel, R. (2017). Linking scientific disciplines: Hydrology and social sciences. *Journal of Hydrology*, *550*, 441-452. https://doi.org/10.1016/j.jhydrol.2017.05.008

Shao, G. P., & Bishop, I. J. (2025). Citizen science in river monitoring: A systematic literature review of the whys and hows. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1609084

Shchepetkin, A. F., & McWilliams, J. C. (2003). A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. *Journal of Geophysical Research: Oceans*, *108*(C3). https://doi.org/10.1029/2001JC001047

Shine, K. P. (1984). Parametrization of the shortwave flux over high albedo surfaces as a function of cloud thickness and surface albedo. *Quarterly Journal of the Royal Meteorological Society*, *110*(465), 747-764. https://doi.org/10.1002/qj.49711046511

Simon, D. F., Munoz, G., Dinh, Q. T., Duy, S. V., Kavanagh, K., Smith, R., Husk, B., & Sauvé, S. (2023). Adopt a Lake: Successfully Tracking Harmful Cyanobacterial Blooms in Canadian Surface Waters Through Citizen Science. *Citizen Science: Theory and Practice*, *8*(1). https://doi.org/10.5334/cstp.655

Smagorinsky, J. (1963). *GENERAL CIRCULATION EXPERIMENTS WITH THE PRIMITIVE EQUATIONS*. https://journals.ametsoc.org/view/journals/mwre/91/3/1520-0493_1963_091_0099_gcewtp_2_3_co_2.xml

Smith, L. T. (2016). *A descolonizar las metodologías. Investigación y pueblos indígenas: A descolonizar las metodologías. Investigación y pueblos indígenas*. LOM Ediciones.

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, *10*(2), 126-139. https://doi.org/10.1065/espr2002.12.142

Sobarzo, M. B., Figueroa, D., & Arcos, D. R. (1997). The Influence of Winds and Tides in the Formation of Circulation Layers in a Bay, a Case Study: Concepción Bay, Chile. *Estuarine, Coastal and Shelf Science*, *45*(6), 729-736. https://doi.org/10.1006/ecss.1997.0233

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. *Anthropocene Review*,

2(1), 81-98. http://www.scopus.com/inward/record.url?scp=84996501052&partnerID=8YFLogxK

Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., & Mironov, D. (2010). First steps of a lake model intercomparison project: LakeMIP. *Boreal environment research*, *15*(2), 191. https://search.proquest.com/openview/d60a3674e3599840e062b6afc6aff527/1?pq-origsite=gscholar&cbl=5500736

Suazo, B. (2014). Fragmentación socioespacial en el barrio Boca Sur, San Pedro de la Paz: La necesidad de implementar una planificación participativa. *Universidad de Concepción*.

Sullivan, C. J., Read, J. S., & Hansen, G. J. A. (2025). Climate-driven alterations of lake thermal regimes. *Limnology and Oceanography*, *70*(8), 2348-2364. https://doi.org/10.1002/lno.70128

Sultana, F. (2022). Critical climate justice. *The Geographical Journal*, *188*(1), 118-124. https://onlinelibrary.wiley.com/doi/abs/10.1111/geoj.12417

Szesztay, K. (1974). Water balance and water level fluctuations of lakes. *Hydrological Sciences Bulletin*, *19*(1), 73-84. http://www.tandfonline.com/doi/abs/10.1080/02626667409493872

Tachikawa, T., Hato, M., Kaku, M., & Iwasaki, A. (2011). Characteristics of ASTER GDEM version 2. *2011 IEEE International Geoscience and Remote Sensing Symposium*, 3657-3660. https://doi.org/10.1109/IGARSS.2011.6050017

Taghizadeh, E., Ahmadi-Givi, F., Brocca, L., & Sharifi, E. (2021). Evaluation of satellite/reanalysis precipitation products over Iran. *International Journal of Remote Sensing*, *42*(9), 3474-3497. https://doi.org/10.1080/01431161.2021.1875508

Tavares, M. H., Cunha, A. H. F., Motta-Marques, D., Ruhoff, A. L., Cavalcanti, J. R., Fragoso, C. R., Martín Bravo, J., Munar, A. M., Fan, F. M., & Rodrigues, L. H. R. (2019). Comparison of Methods to Estimate Lake-Surface-Water Temperature Using Landsat 7 ETM+ and MODIS Imagery: Case Study of a Large Shallow Subtropical Lake in Southern Brazil. *Water*, *11*(1), Article 1. https://doi.org/10.3390/w11010168

Tedesco, A. M., López-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Pérez-Hämmerle, K.-V., Brancalion, P. H. S., Wilson, K. A., Oliveira, M., Correa, D. F., Ota, L., Morrison, T. H., Possingham, H. P., Mills, M., Santos, F. C., & Dean, A. J. (2023). Beyond ecology: Ecosystem restoration as a process for social-ecological transformation. *Trends in Ecology & Evolution*, *38*(7), 643-653. https://doi.org/10.1016/j.tree.2023.02.007

Tierney, G. L., Faber-Langendoen, D., Mitchell, B. R., Shriver, W. G., & Gibbs, J. P. (2009). Monitoring and evaluating the ecological integrity of forest ecosystems. *Frontiers in Ecology and the Environment*, *7*(6), 308-316. https://doi.org/10.1890/070176

Tilgenkamp, A. (2025, agosto 2). *Theil–Sen estimator [online]. MATLAB Central File Exchange.* https://www.mathworks.com/matlabcentral/fileexchange/34308-theil-sen-estimator

Torres, R. (2023, enero 24). Resistance In Chile's "State Of Exception". *Majority Post*. https://majoritypost.com/resistance-in-chiles-state-of-exception/

Torres, R., Azócar, G., Gallardo, R., & Mendoza, J. (2022). *Water Extractivism and Decolonial Struggles in Mapuche Territory, Chile*. *15*(1).

Torres, R., Azócar, G., Rojas, J., Montecinos, A., & Paredes, P. (2015). Vulnerability and resistance to neoliberal environmental changes: An assessment of agriculture and forestry in the Biobio region of Chile (1974–2014). *Geoforum*, *60*, 107-122. https://doi.org/10.1016/j.geoforum.2014.12.013

Traganos, D., Poursanidis, D., Aggarwal, B., Chrysoulakis, N., & Reinartz, P. (2018). Estimating Satellite-Derived Bathymetry (SDB) with the Google Earth Engine and Sentinel-2. *Remote Sensing*, *10*(6), Article 6. https://doi.org/10.3390/rs10060859

Trenberth, K. E., & Hoar, T. J. (1996). The 1990–1995 El Niño-Southern Oscillation Event: Longest on Record. *Geophysical Research Letters*, *23*(1), 57-60. https://doi.org/10.1029/95GL03602

Troitskaya, Y., Rybushkina, G., Soustova, I., Balandina, G., Lebedev, S., & Kostianoy, A. (2012). Adaptive retracking of Jason-1 altimetry data for inland waters: The example of the Gorky Reservoir. *International Journal of Remote Sensing*, *33*(23), 7559-7578. https://doi.org/10.1080/01431161.2012.685972

UCM. (2024). *Earth Engine Data Catalog: TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces [online]. Merced, University of California Merced.* https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE#bands

University of North Carolina. (2025). *Mediciones en Lagos Red Ciudadana y Satelital*. LOCSS. https://www.locss.org/es

Upreti, G. (2023). Autopoiesis, Organizational Complexity, and Ecosystem Health. En G. Upreti (Ed.), *Ecosociocentrism: The Earth First Paradigm for Sustainable Living* (pp. 91-110). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-41754-2_5

Urrutia, R., Almanza, V., & Woelfl, S. (2022, septiembre 8). *Seminario proyecto: Levantamiento de información limnológica para la propuesta de NSCA de lagos nor-patagónicos* [[Discurso principal]. Seminario en línea.].

US EPA. (2011). *National wetland condition assessment: Field operations manual*.

US EPA. (2025). *Factsheets on Water Quality Parameters*. https://www.epa.gov/awma/factsheets-water-quality-parameters

US EPA, O. (2015, abril 16). *What is the National Lakes Assessment?* [Overviews and Factsheets]. https://www.epa.gov/national-aquatic-resource-surveys/what-national-lakes-assessment

USGS. (2025). *U.S. Geological Survey*. https://www.usgs.gov/

Valdés-Pineda, R., Cañón, J., & Valdés, J. B. (2018). Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals. *Journal of Hydrology*, *556*, 1153-1170. https://doi.org/10.1016/j.jhydrol.2017.01.031

Valdés-Pineda, R., Valdés, J. B., Diaz, H. F., & Pizarro-Tapia, R. (2016, junio 30). *Analysis of spatio-temporal changes in annual and seasonal precipitation variability in South America-Chile and related ocean-atmosphere circulation patterns.* | *EBSCOhost*. https://doi.org/10.1002/joc.4532

Vela, S. R. (2019). Método mayéutica y consultorías filosóficas en el siglo XXI. *Phainomenon*, *18*(2), 141-154. https://doi.org/10.33539/phai.v18i2.1745

Vera, R., & Rosner, C. (2020). *Recopilación y análisis de antecedentes para la revisión de la Norma Secundaria de Calidad Ambiental del lago Llanquihue*. ResearchGate. https://doi.org/10.13140/RG.2.2.29431.80801

Vergara Díaz, G., Vázquez, V. S., & Herrera Machuca, M. Á. (2018). Análisis del ambio temporal y espacial del uso del suelo en la región Centro-sur de Chile. *Ciência Florestal*, *28*, 1831-1844. https://www.scielo.br/j/cflo/a/rtg7y6cGShDvQkMjWL7k47Q/?lang=es&format=html&stop=next

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). *A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index*. https://doi.org/10.1175/2009JCLI2909.1

Vlasova, T., Petrov, A. N., & Volkov, S. (2021). Rethinking Sustainability Monitoring in the Arctic by Linking Resilience and Sustainable Development in Socially-Oriented Observations: A Perspective. *Sustainability*, *13*(1), Article 1. https://doi.org/10.3390/su13010177

Voulvoulis, N., Giakoumis, T., Hunt, C., Kioupi, V., Petrou, N., Souliotis, I., Vaghela, C., & binti Wan Rosely, WIH. (2022). Systems thinking as a paradigm shift for sustainability transformation. *Global Environmental Change*, *75*, 102544. https://www.sciencedirect.com/science/article/pii/S0959378022000826

Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., & Bierkens, M. F. P. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, *37*(20). https://doi.org/10.1029/2010GL044571

Wadoux, A. M. J.-C., & Minasny, B. (2024). Some limitations of the concordance correlation coefficient to characterise model accuracy. *Ecological Informatics*, *83*, 102820. https://doi.org/10.1016/j.ecoinf.2024.102820

Wakana, I., Kadono, Y., Urabe, J., Tamura, Y., Suzuki, Y., Yamada, H., Oyama, Y., Wada, K., Hasegawa, T., & Ohara, M. (2023). Varying stages of ecological succession in lakes subdivided by volcanic eruptions at Akan Caldera, Japan. *Hydrobiologia*, *850*(18), 3919-3933. https://doi.org/10.1007/s10750-023-05231-5

Wang, H., Qi, Y., Lian, X., Zhang, J., Yang, R., & Zhang, M. (2022). Effects of climate change and land use/cover change on the volume of the Qinghai Lake in China. *Journal of Arid Land*, *14*(3), 245-261. https://doi.org/10.1007/s40333-022-0062-4

Warner, S., Blanco Ramírez, S., de Vries, S., Marangu, N., Ateba Bessa, H., Toranzo, C., Imaralieva, M., Abrate, T., Kiminta, E., Castro, J., de Souza, M. L., Ghaffar Memon, A., Loiselle, S., & Juanah, M. S. E. (2024). Empowering citizen scientists to improve water quality: From monitoring to action. *Frontiers in Water*, *6*. https://doi.org/10.3389/frwa.2024.1367198

Westra, L., & Lemons, J. (2012). *Perspectives on Ecological Integrity*. Springer Science & Business Media.

Wetzel, R. G. (2001). *Limnology: Lake and River Ecosystems*. Gulf Professional Publishing.

Williams, J. (2021). *Climate change is racist: Race, privilege and the struggle for climate justice*. Icon Books. https://books.google.es/books?hl=es&lr=&id=RIQiEAAAQBAJ&oi=fnd&pg=PP8&dq=Williams,+J.+(2021).+Climate+change+is+racist:+Race,+privilege+and+the+struggle+for+climate+justice.+Icon+Books.&ots=NWw2BQCCgc&sig=7BuVe4PrQpNz7d1MptUcKTYDbj4

Willmott, C. J. (1981). On the Validation of Models. *Physical Geography*, *2*(2), 184-194. https://doi.org/10.1080/02723646.1981.10642213

Winkler, K., Fuchs, R., Rounsevell, M., & Herold, M. (2021). Global land use changes are four times greater than previously estimated. *Nature Communications*, *12*(1), 2501. https://www.nature.com/articles/s41467-021-22702-2

Winter, T. C. (1981). Uncertainties in Estimating the Water Balance of Lakes. *JAWRA Journal of the American Water Resources Association*, *17*(1), 82-115. https://doi.org/10.1111/j.1752-1688.1981.tb02593.x

WISDOM. (2025). *Objectives of the WISDOM Project*. https://wisdom.eoc.dlr.de/en/content/objectives-wisdom-project.html

WMO. (2025). *WMO Information System (WIS)*. https://old.wmo.int/extranet/pages/prog/www/WIS/

WMOa. (2025). *Observing Systems Capability Analysis and Review Tool (OSCAR)*. https://oscar.wmo.int/surface/#/

Wolodarsky-Franke, A., & Díaz, S. (2011). Cordillera de Nahuelbuta. *Reserva Mundial de Biodiversidad. Valdivia, Chile: WWF*.

Wongchuig, S., Carlo Espinoza, J., Condom, T., Junquas, C., Sierra, J. P., Fita, L., Sörensson, A., & Polcher, J. (2023). Changes in the surface and atmospheric water budget due to projected Amazon deforestation: Lessons from a fully coupled model simulation. *Journal of Hydrology*, *625*, 130082. https://doi.org/10.1016/j.jhydrol.2023.130082

Woods, S. (2025). How citizen science can help to solve the global freshwater crisis. *Nature*, *644*(8077), 582-582. https://doi.org/10.1038/d41586-025-02614-7

Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews Earth & Environment*, *1*(8), 388-403. https://doi.org/10.1038/s43017-020-0067-5

Woolway, R. I., Sharma, S., & Smol, J. P. (2022). Lakes in Hot Water: The Impacts of a Changing Climate on Aquatic Ecosystems. *BioScience*, *72*(11), 1050-1061. https://doi.org/10.1093/biosci/biac052

Woolway, R. I., Tong, Y., Feng, L., Zhao, G., Dinh, D. A., Shi, H., Zhang, Y., & Shi, K. (2024). Multivariate extremes in lakes. *Nature Communications*, *15*(1), 4559. https://doi.org/10.1038/s41467-024-49012-7

Wu, J., Li, W., Du, H., Wan, Y., Yang, S., & Xiao, Y. (2025). Nonlinear responses of coupled socioecological systems to land use and climate changes in the Yangtze river basin. *Scientific Reports*, *15*(1), 6940. https://doi.org/10.1038/s41598-025-92084-8

Wurtsbaugh, W. A., Paerl, H. W., & Dodds, W. K. (2019). Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *WIREs Water*, *6*(5), e1373. https://doi.org/10.1002/wat2.1373

Xu, J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Xu, W. (2022). Ecological Integrity Evaluation of Organically Evolved Cultural Landscape. *Mobile Information Systems*, *2022*(1), 9554359. https://doi.org/10.1155/2022/9554359

Xu (徐菊英), J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various

definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Yang, J., & Du, X. (2017). An enhanced water index in extracting water bodies from Landsat TM imagery. *Annals of GIS*, *23*(3), 141-148. https://doi.org/10.1080/19475683.2017.1340339

Yang, Xu, M., Li, R., Zhang, L., & Deng, Q. (2020). Estimating the ecological water levels of shallow lakes: A case study in Tangxun Lake, China. *Scientific Reports*, *10*(1), 5637. https://doi.org/10.1038/s41598-020-62454-5

Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J.-F., Wada, Y., & Berge-Nguyen, M. (2023). Satellites reveal widespread decline in global lake water storage. *Science*, *380*(6646), 743-749. https://doi.org/10.1126/science.abo2812

Zelený, J., Mercado-Bettín, D., & Müller, F. (2021). Towards the evaluation of regional ecosystem integrity using NDVI, brightness temperature and surface heterogeneity. *Science of The Total Environment*, *796*, 148994. https://www.sciencedirect.com/science/article/pii/S0048969721040663

Zhang, M., Lee, H., SHUM, C. K., Alsdorf, D., Schwartz, F., Tseng, K.-H., Yi, Y., Kuo, C.-Y., Tseng, H.-Z., Braun, A., Calmant, S., Filizola, N., & Seyler, F. (2010). Application of retracked satellite altimetry for inland hydrologic studies. *International Journal of Remote Sensing*, *31*(14), 3913-3929. https://doi.org/10.1080/01431161.2010.483495

Zhao, G., Li, Y., Zhou, L., & Gao, H. (2022). Evaporative water loss of 1.42 million global lakes. *Nature Communications*, *13*(1), 3686. https://doi.org/10.1038/s41467-022-31125-6

Zhao, Y., Feng, D., Yu, L., Wang, X., Chen, Y., Bai, Y., Hernández, H. J., Galleguillos, M., Estades, C., Biging, G. S., Radke, J. D., & Gong, P. (2016). Detailed dynamic land cover mapping of Chile: Accuracy improvement by integrating multi-temporal data. *Remote Sensing of Environment*, *183*, 170-185. https://www.sciencedirect.com/science/article/pii/S0034425716302188

Zhou, J., Leavitt, P. R., Rose, K. C., Wang, X., Zhang, Y., Shi, K., & Qin, B. (2023). Controls of thermal response of temperate lakes to atmospheric warming. *Nature Communications*, *14*(1), 6503. https://doi.org/10.1038/s41467-023-42262-x

Zhu, J., Peng, S., Shen, X., Lin, Z., Gong, L., Zhang, R., & Huang, B. (2024). Multiple scale impacts of land use intensity on water quality in the Chishui river source area. *Ecological Indicators*, *166*, 112396. https://doi.org/10.1016/j.ecolind.2024.112396

Zhu, L., Ju, J., Qiao, B., Liu, C., Wang, J., Yang, R., Ma, Q., Guo, L., & Pang, S. (2025). Physical and biogeochemical responses of Tibetan Plateau lakes to climate change. *Nature Reviews Earth & Environment*, *6*(4), 284-298. https://doi.org/10.1038/s43017-025-00650-5

Capítulo III

A Google Earth Engine application to retrieve long-term surface temperature for medium to small-sized lakes. Case: Nahuelbutan lakes.

Chapter based on the article: Pedreros-Guarda, M., Abarca-del-Río, R., Escalona, K., García, I., & Parra, Ó. (2021). A Google Earth Engine application to retrieve long-term surface temperature for small lakes. Case: San Pedro lagoons, Chile. *Remote Sensing*, *13*(22), 4544.

Abstract

Lake surface water temperature (LSWT) is a crucial water quality parameter that modulates many physical, chemical, and biological processes in lakes and reservoirs. Long-term monitoring is essential to understand thermal dynamics, yet in-situ measurements are often limited, especially in medium to small-sized lakes. This study presents a methodology to retrieve multi-decadal LSWT series using Landsat 7, 8, and 9 imagery processed on the Google Earth Engine (GEE) platform at 30 m spatial resolution. The method was applied to the Nahuelbutan lakes in south-central Chile, with

calibration performed for two lakes with continuous historical records: Lagoon Grande de San Pedro and Lake Lanalhue, using in-situ temperature measurements. Statistical evaluation showed strong agreement between satellite-derived and in-situ series ($R^2 \geq 0.87$, Willmott's index ≥ 0.97), with low *NRMSE* (less than 0.12) and P_{BIAS} close to zero. The resulting climatologies reveal a coherent seasonal cycle across all lakes, with summer maxima (up to ~26 °C) and winter minima (~8 °C). The approach demonstrates that GEE-based processing of Landsat thermal data provides a reliable, scalable, and cost-effective solution for reconstructing LSWT patterns where direct monitoring is scarce. This methodology can be readily transferred to other variables and regions. Integrating it with additional satellite missions could enhance long-term inland water temperature monitoring under climate change scenarios.

1. Introduction

Today, lakes around the world share the same problem: an increase in eutrophication, related to rising levels of nutrients, mainly phosphorus and nitrogen (Parra et al., 2003). Nutrient concentration, water temperature and radiation modulate the frequency of harmful algal blooms (HABs), which have been increasing worldwide (Parra et al., 2016).

LSWT can be interpreted as an integrative indicator of hydrological integrity because it summarizes the lake's thermal regime, which governs

stratification strength and duration and, in turn, constrains vertical mixing, oxygen renewal, and nutrient recycling (Beutel et al., 2001; Meerhoff et al., 2022; Piccolroaz et al., 2013, 2024a; Woolway et al., 2022). LSWT is especially informative because bloom frequency and intensity are jointly modulated by nutrient availability, water temperature, and radiation (Abarzúa et al., 2020; Alaniz et al., 2021; Almanza et al., 2016; Ascencio et al., 2018; Parra et al., 2016; Parra et al., 2003). This indicator is also consistent with monitoring practice, where water temperature is explicitly considered among physico-chemical elements for ecosystem status assessment and temperature criteria are used to protect aquatic life (European Environment Agency, 2018; US EPA, 2025), detailed as follows.

Under the integrated basin management framework, several countries conduct frequently ecosystem status assessments, monitoring LSWT. For example, the European Environment Agency evaluates ecological status for rivers, lakes and transitional and coastal waters, using several indicators that include biological quality elements and physico-chemical, including water temperature (European Environment Agency, 2018). The US Environmental Protection Agency (EPA) also includes water temperature in their aquatic ecosystems monitoring. They even recommends a temperature criteria based on the ranges accepted by aquatic life (US EPA, 2025). In Latin American cases, such as Brazil or Chile, temperature is usually a parameter measured in monitoring campaigns, and is normatively used to regulate effluents,

although it is not used as a status indicator (Agência Nacional de Águas e Saneamento Básico (ANA), 2025; DGA, 2025b).

The traditional method to measure LSWT consists of collecting field samples. However, besides being a localized and heterogeneous method between measurement stations, monitoring water quality in a large lake through direct sampling is logistically costly and economically inefficient and does not cover the entire area at the same time (Membrillo-Abad et al., 2016a). This explains why spatial remote sensing methods, which obtain LSWT over large areas, play a fundamental role today (Elachi & Zyl, 2021). Remote sensing has been successfully used for the past 40 years to estimate water quality globally.

Currently, there are local and global LSWT databases built using remote sensing techniques. Several efforts have been made to generate regional lake databases. For example, there is a long-term LSWT database for the Tibetan Plateau using AVHRR (Lieberherr & Wunderle, 2018), another focused on subalpine lakes using a variety of sensors (Pareeth et al., 2016). At the global level, Copernicus (COPERNICUS, 2025) monitors the Earth using satellite and in-situ sensors. LSWT data for 258 large lakes worldwide (surface > 500 km²) for the period 1995–2009 is freely available in ESA (2025). Although the project could be extended to medium and small lakes, to the best of our knowledge, no global databases provide temperature data for these cases. This article is intended for individual researchers who wish to obtain

LSWT using remote sensing methods for a specific lake, especially for medium to small-sized lakes.

The wide spatial extent provided by satellite temperature is an advantage over other types of temperature measurements. Generally, the satellite image covers the entire surface of small and medium-sized lakes, and in the case of large lakes or marine applications, this can be resolved by combining several images into a mosaic. Secondly, spatial fields with a resolution of 30 m are obtained using Landsat images, which could be further reduced (down to 10 m) using newer satellites such as Sentinel.

However, calculating LSWT from remote sensing images is a complex and time-consuming task due to the data processing chain (Kumar & Mutanga, 2018). Currently, the Google Earth Engine (GEE) platform offers a useful solution. It is an innovative tool for geospatial analysis that uses cloud computing. The user does not need a powerful computer, only a basic internet connection (Kumar & Mutanga, 2018). GEE enables the analysis of satellite data files (Amani et al., 2020), satellite bathymetry estimation (Traganos et al., 2018), and drought evaluation (Sazib et al., 2018), among many other applications. This work used the GEE platform to extract LSWT in any lake, particularly those of small or medium size (surface < 100 km² (Solheim et al., 2019)). This small spatial scale represents an additional challenge, as not just any satellite is suitable. A sensor with appropriate spatial resolution is required.

Landsat files, the most widely used dataset in GEE (Kumar & Mutanga, 2018), have proven useful for this purpose (Ogilvie et al., 2018; Prats et al., 2018; Randrianiaina et al., 2018; Tavares et al., 2019). They have a temporal resolution of 16 days and a spatial resolution of 30 m, except for their thermal bands, which have a spatial resolution of 60–120 m. Additionally, Landsat 7 and 8 had an 8-day offset, so together they provided four (4) satellite images every 32 days. Landsat 9 was launched in October 2021, replacing Landsat 7. Thus, Landsat 8 and 9 now jointly provide four (4) images every 32 days (USGS, 2025). Landsat image collections 1–9 are available through the GEE platform. These collections are in their original version (in digital numbers) (e.g., EEDCa, 2025). For the same collections, there is also the top-of-atmosphere (ToA) reflectance and brightness temperature product (e.g., EEDCb, 2025). It is even possible to find the surface reflectance and brightness temperature product, which includes atmospheric correction and is ready to use (e.g., EEDCc, 2025).

In this study, we focus on the Nahuelbutan lakes, a set of medium to small-sized lacustrine systems in south-central Chile that have been subject to both anthropogenic and natural pressures (Alaniz et al., 2021; Parra et al., 2003). Previous research in the region has documented recurrent harmful algal blooms and signs of eutrophication (Abarzúa et al., 2020; Almanza et al., 2016; Ascencio et al., 2018), underscoring the importance of long-term thermal

characterization as a baseline for understanding ecosystem processes and improving water quality forecasting.

This work has two objectives. First, to represent the spatial and temporal patterns of LSWT in medium to small-sized lakes of the coastal - Nahuelbuta mountain range system, using multi-decadal Landsat 7, 8, and 9 archives with the motivation to widen the state of the art of Nahuelbutan lakes. Second, to validate the remote sensing methodologies, with the motivation of being able to easily include water temperature as an ecological status indicator. Validation is performed in two representative systems: Lagoon Grande de San Pedro and Lake Lanalhue, which have the longest and most complete in-situ temperature records in the area. For this task, R-squared (R^2), normalized root mean square error *(NRMSE*), and Willmott's index (*d*) (Willmott, 1981) are used. The approach leverages Google Earth Engine (GEE) for data processing and applies a calibration framework based on statistical comparison with in-situ observations, ensuring accurate reconstruction of LSWT series. This allows for the generation of seasonal and annual climatologies, as well as the assessment of inter-lake variability. By providing long-term, spatially explicit LSWT datasets for a group of lakes under pressure from climate change and eutrophication, the study addresses the current gap in thermal characterization of medium to small-sized lakes in the Southern Hemisphere.

This chapter allows achieving the second specific objective of this doctoral thesis: Analyze the spatiotemporal water quality of the Nahuelbutanos Lakes since 1950 using the surface temperature of the lake water. It also seeks to contribute in testing the third hypothesis (H3): Remote sensing and numerical modeling tools can be integrated into environmental monitoring.

2. Study area

The study area is located in south-central Chile, within the Biobío Region and near the Pacific Ocean (Figure III.1). This region is characterized by a warm-temperate climate with warm, dry summers and rainfall concentrated in winter (Bravo Orrego, 2018; Kottek et al., 2006; Sarricolea et al., 2017). Besides climate change, in recent years, central-Chile has been severely affected by the ongoing Megadrought, which began in 2010 and has resulted in a 25–45% reduction in precipitation (Garreaud et al., 2020), causing significant climatic stress over the past fifteen years.

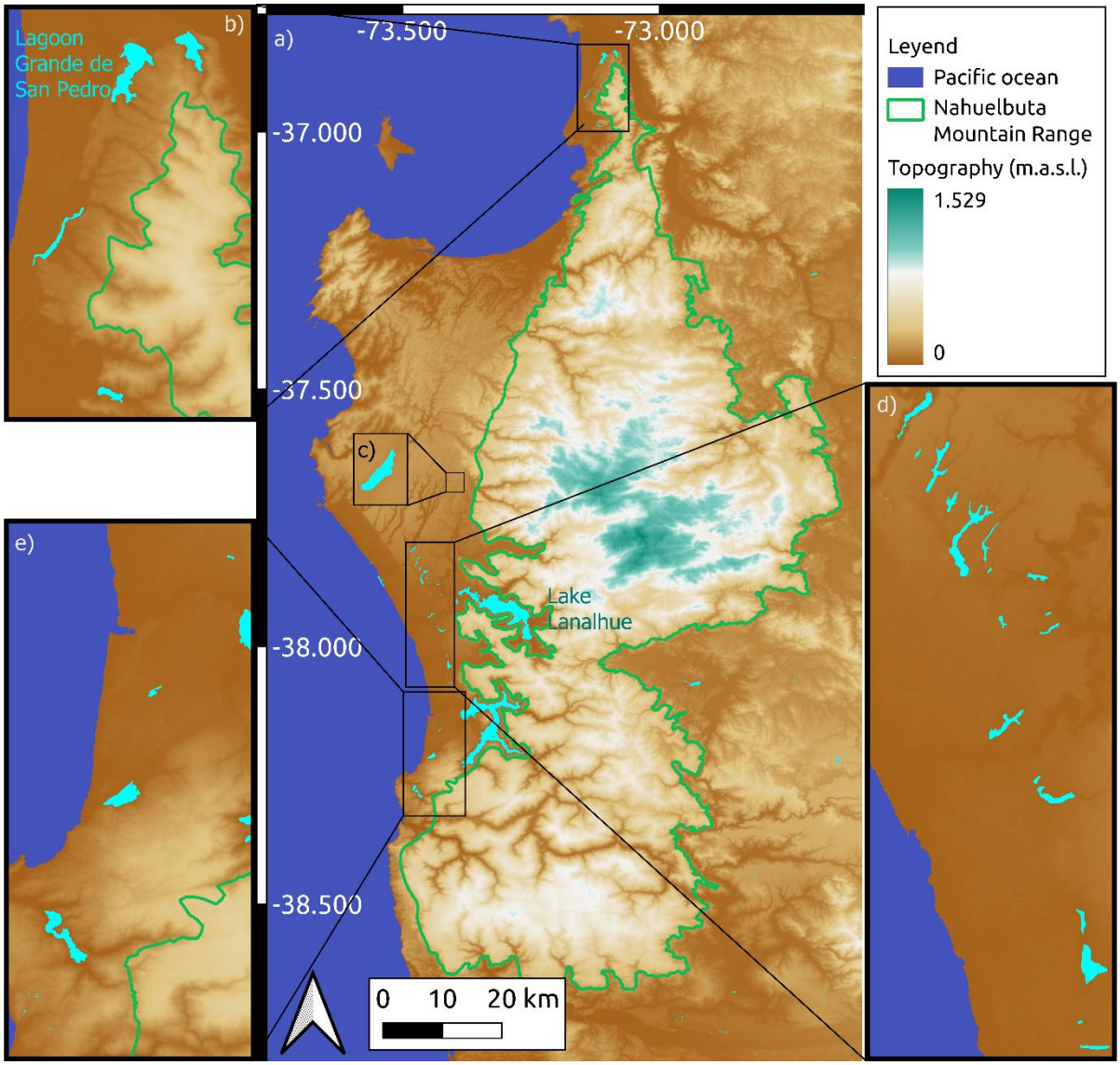


Figure III.1. a) Study area. b) Zoom into northern Nahuelbutan lakes. c) Zoom into Lagoon Antihuala. d-e) Zoom into southern Nahuelbutan lakes.

Within this region lies the Nahuelbuta mountain range, whose western slope drains into several small exorheic coastal basins. This range has given rise to at least 32 coastal lacustrine systems, collectively known as the Nahuelbutan lakes. Locally, these water bodies are referred to as either “lakes”

or “lagoons”, regardless of their size. These lentic systems share similar climatic and geological characteristics and do not experience winter ice cover (Parra et al., 2003). The Nahuelbuta mountain range has historically served as a biodiversity refuge during past climate changes and remains a conservation priority within the Chilean Mediterranean biodiversity hotspot (Arroyo et al., 2006; Wolodarsky-Franke & Díaz, 2011).

The environmental history of the Nahuelbutan lakes can be traced through key phases: i) 1850–1880 – Clearing and burning of native forest for agriculture (Otero Durán, 2012). ii) Post-1974 – Expansion of forestry plantations, promoted by Decree Law No. 701 (Aguayo et al., 2009; Araya, 2019; Lara et al., 2012; Martínez Retureta, 2021). iii) Since 1975 – Urban development, particularly around Concepción (Rojas Quezada et al., 2009).

The Introducción of this doctoral tesis, along with the Appendix III.I, details the institutional system that safeguards the water quality of Chile's lake systems. Within this framework, historical water temperature data collected by the DGA are available. LSWT is reconstructed for most of the Nahuelbutan lakes. However, model calibration and validation are performed using the two systems with the most extensive and continuous historical temperature records: Laguna Grande de San Pedro and Lake Lanalhue. Table III.1 summarizes the main physical, ecological, and social characteristics of these two lakes.

Table III.1. Main physical, ecological and environmental characteristics of Lakes Laguna Grande de San Pedro and Lanalhue (Almanza et al., 2016; O. Parra et al., 1999; O. Parra, 2003a)

Characteristic	Grande de San Pedro	Lanalhue
Lake area (km²)	1.55	31.9
Basin area (km²)	12.7	327.43
(Basin area / lake area) ratio	8.2	10.2
Máx length (km)	2.7	9.6
Máx width (km)	1.4	4.3
Average depth (m)	8.3	13.1
Máx depth (m)	13.5	26
Perimeter (km)	9.4	58.6
Precipitation (mm/year)	1800	2300
Height (m.a.s.l.)	4	12
Renovation time (months)	24	12.5
Trophic degree	Eutrophic – Hiper eutrophic	Eutrophic
Seasonal stratification	No	Yes
Main watershed use	Forestry, recreational, tourism, residential	Forestry, recreational, tourism, residential and agriculture.
Main lake use	Recreational, Tourism, Receptor	
Algal bloom	Yes	
Direct tributaries		11
Alimentation	Pluvial	

3. Data and methods

3.1. Data

3.1.1. In-situ

3.1.1.1. LSWT data

The Chilean Directorate of Water Resources (DGA) provides LSWT time series. The DGA is a public institution responsible for managing, verifying, and disseminating water-related information in Chile. It provides physicochemical and biological water quality parameters (e.g. temperature, specific conductivity, pH, dissolved oxygen, oxygen saturation, chlorophyll-a, turbidity percentage, and Secchi disk transparency) for different Chilean lakes (DGA, 2025b).

In the study area, the sampling stations with longest time series of physicochemical parameters are located in Laguna Grande de San Pedro (stations Centro (C), Desagüe (D), and Sur (S)) and in Lake Lanalhue (stations Puerto Peleco (PP), Frente Hostería (FH), Playa Blanca (PB), Sector Centro (SC), and Puerto Manzano (PM)) (see Table III.2). There are continuous historical LSWT series between 2000 and 2010. Measurements are taken at different times between 9 a.m. and 6 p.m. (UTC-4). Unfortunately, these stations are not currently operational. Although some in-situ samples have

been taken since 2014, they are in other locations and sporadic, with seasonal or no measurements per year. The same occurs between 1988 and 1999. Therefore, the period used is between 1999 and 2010, where there is generally one seasonal measurement. A summary of the stations can be found in Table III.2.

Table III.2. In-situ LSWT sampling stations used and their coordinates in decimal degrees: Desagüe (D), Centro (C), Sur (S), Puerto Peleco (PP), Frente Hostería (FH), Playa Blanca (PB), Sector Centro (SC), and Puerto Manzano (PM). Seasonal sampling (4 times per year). Available data: LSWT in the period 1988–2013. Used period 2000–2010.

Station	Coordinates	Period
D	−36.8495, −73.1091	1988–2013
C	−36.8620, −73.1136	
S	−36.8688, −73.1161	
PP	-37.8867, -73.3735	2000 - 2014
FH	-37.9173, -73.3105	
PB	-37.9348, -73.2646	
SC	-37.9201, -73.3130	
PM	-37.9751, -73.2555	

3.1.2. Landsat data

The USGS (U.S. Geological Survey) provides, through the Google Earth Engine (GEE) platform, all satellite image collections from the Landsat family. The following collections are extracted between 1999 and 2024: USGS

Landsat (L) 7, 8, and 9 Level 2, Collection 2, Tier 1 (Table III.3). The Landsat satellite missions always pass over the study area at approximately 10:40 a.m. (local time, UTC-4) (this information can be obtained from the metadata of each image).

Table III.3. Satellite data. Available and used period. From the latter: resulting images after applying Tier 1 filters and cloud cover <30%.

Colection	Available period (DD/MM/AAAA)	Used period (DD/MM/AAAA)	Filtered images
Landsat 7 Level 2, Collection 2, Tier 1	1999 – 2024	2000 - 2024	198
Landsat 8 Level 2, Collection 2, Tier 1	2013 – 2025		133
Landsat 9 Level 2, Collection 2, Tier 1	2021 – 2025		34

The collections already include surface brightness temperature. They have been corrected using the Landsat Ecosystem Disturbance Adaptive Processing System and Land Surface Reflectance Code software. The USGS resampled the collections to a spatial resolution of 30 m using cubic convolution. The collections are then pre-filtered, separating them into higher quality images (Tier 1), lower quality (Tier 2), and real-time (USGS). In our case, we selected the Tier 1 collections. Then, we filtered these collections by selecting images with cloud cover <30%. Additionally, the QA band is used. This band contains low-quality pixels, which we remove accordingly. We also remove outliers from the series. The term ‘outlier’ refers to values that exceed three median absolute deviations. The code is available in Pedreros-Guarda, (2025).

3.2. Methods

3.2.1. Validation

We conducted a validation among the three satellite series (L7, 8, and 9) and the in-situ data. The analysis is performed between different pairs of series. L7 shares a period with the in-situ data (2000–2010), so it is compared with it. On the other hand, the remaining series are compared with each other over common periods: L7–L8 (2013-2024) and L8–L9 (2021-2024). We employed a set of statistics: square of the correlation coefficient (R^2), normalized root-mean-square error (*NRMSE*), Modified Willmott coefficient (*d*) and P_{BIAS}. Their equations are shown as follows.

$$R^2 = \left(\frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \right)^2 \quad (1)$$

$$NRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}}{y_{max} - y_{min}} \quad (2)$$

$$d = 1 - \frac{\sum_{i=1}^{n}|y_i - x_i|}{\sum_{i=1}^{n}(|y_i - \bar{x}| + |x_i - \bar{x}|)} \quad (3)$$

$$P_{BIAS} = \frac{\sum_{i=1}^{n}(x_i - y_i)}{\sum_{i=1}^{n}(x_i)} \quad (4)$$

, where x and y are the observed and simulated time series, that is, in-situ and satellite LSWT or the two satellite LSWT datasets, and $\bar{x}$ and $\bar{y}$ are their mean values. n is the number of observations.

R^2 , the most widely applied measure, represents the proportion of shared variance (Onyutha, 2021). It ranges from 0 to 1 and values greater than 0.5 are considered acceptable in watershed simulations (Moriasi et al., 2007). $NRMSE$ indicates the normalized overall difference between two datasets (Chicco et al., 2021). An acceptable range is between 0 and 20% (Maniruzzaman et al., 2015a). d is the proportion of agreement between two datasets. 0 represents no agreement, and 1, perfect agreement (Willmott, 1981). P_{BIAS} measures the average tendency of the simulated data to their observed counterparts. Positive values indicate an overestimation of observation, while negative values indicate an underestimation. The optimal value of P_{BIAS} is 0.0, with low-magnitude values indicating accuracy (G. H. Fang et al., 2015).

3.2.2. LSWT model

We fit linearly (calibrate) the LSWT series between them and with the in-situ series. We keep the following in mind. The Landsat 7-LSWT series can be directly calibrated against the real data since they share the same time period from 1999 to 2009. However, the L8 series does not begin until 2013, when no in-situ data are available. As a result, the in-situ data cannot be used

to calibrate the Landsat 8 series. However, the Landsat 7-LSWT series is present throughout the period 1999–2021). Then using the already calibrated Landsat 7-LSWT series, it is possible to calibrate Landsat 8. Then, using Landsat 8, it is possible to calibrate Landsat 9.

3.2.3. Spatial and temporal analysis of LSWT

LSWT images were extracted for the Nahuelbutan lakes from Landsat 7 to 9 files to analyze their spatial and seasonal patterns. Unfortunately, Grande de San Pedro and Lanalhue are the only Nahuelbutan lakes with continuous historical series available for calibration. Therefore, LSWT for these two water bodies was adjusted and presented as historical series. Climatologies for the period 2013–2024 were built, based on Landsat 8, as it offers the longest continuous record within the study period and presents no spatial gaps (unlike Landsat 7). In the case of LG and LL, temporal climatologies were based on LSWT values extracted around in-situ stations. To analyze spatial patterns, the average annual and seasonal climatologies for these two water bodies were built. To analyze seasonal patterns, the boxplot of the monthly climatology of the LSWT in the lakes is built.

A similar procedure is followed for the rest of the lakes but based solely on Landsat 8 satellite-derived LSWT information (LSWT phenology). To analyze spatial inter-lake LSWT patterns, the average annual climatologies are built. To analyze seasonal cycles, the domain-average LSWT was used to

construct temporal climatologies. In the latter case, only lakes with names in the national lake inventory are used. These lakes can be seen in Figure 7. Their names and short-names used are the following: Lagoon Grande de San Pedro (LG), Lagoon Chica de San Pedro (LCh), Lagoon La Posada (LP), Lagoon Quiñenco (LQ), Lagoon Antihuala (LAn), Lagoon Lencan (LLen), Lagoon Redonda (LRed), Lagoon Bilbilco (LBil), Lagoon Pilquichome (LPil), Lagoon Catripahue (LCat), Lagoon Lloncao (LLlon), Lagoon Loncotripa (LLon), Lagoon Trilaco (LTri), Lagoon Anilauquén (LAni), Lagoon Malalquehue o Las Toscas (LMaL), Lagoon Tiqueregue (LTiq), Lagoon Puyehue (LPuy), Lagoon Trancalco (LTran), Lagoon Los Batros (LLBat), Lagoon Antiquina (LAnt), Lagoon Antiquina 2 (LAnt2), Lake Lanalhue (LL), Lagoon Machilhue (LMach), Lagoon Quilaco (LQuil), Lagoon Junquillos (LJun), Lake Lleulleu (LLl), Lagoon de los Cisnes (LLCis), Lagoon Butaco (LBut), Lagoon Quidico (LQuid), Lagoon Aurora (LAur), Lagoon Los Batros 2 (LLBat2), Lagoon Quilamalin (LQuilam). To do this procedure, lakes smaller than 60m have not been considered, as a 30m buffer has been applied in order to ensure only water pixels.

The methodology is summarized in Figure III.2.

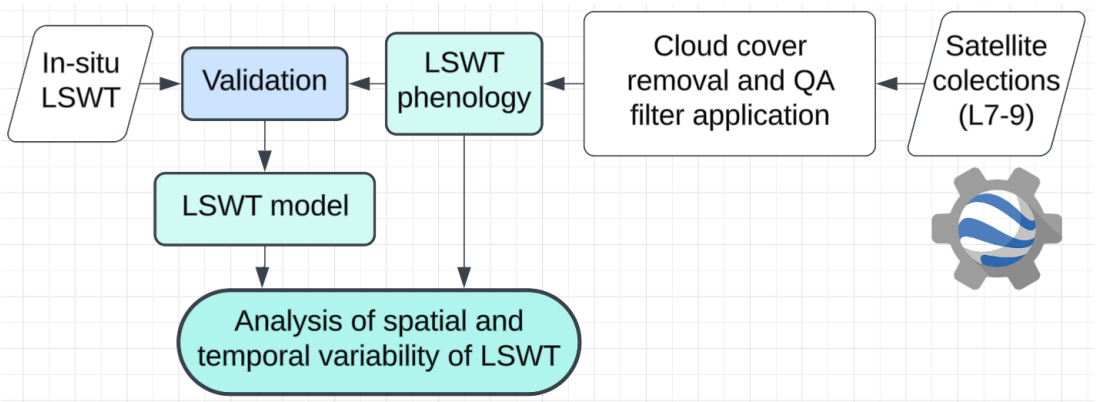


Figure III.2. Flow diagram of the methodology.

4. Results

4.1. Validation

Each LSWT series exhibits the same seasonal fluctuation, with warm peaks during austral summer and cold minimum in winter (Figure III.3). There are differences among datasets associated with their mean difference as reflected in Table III.4.

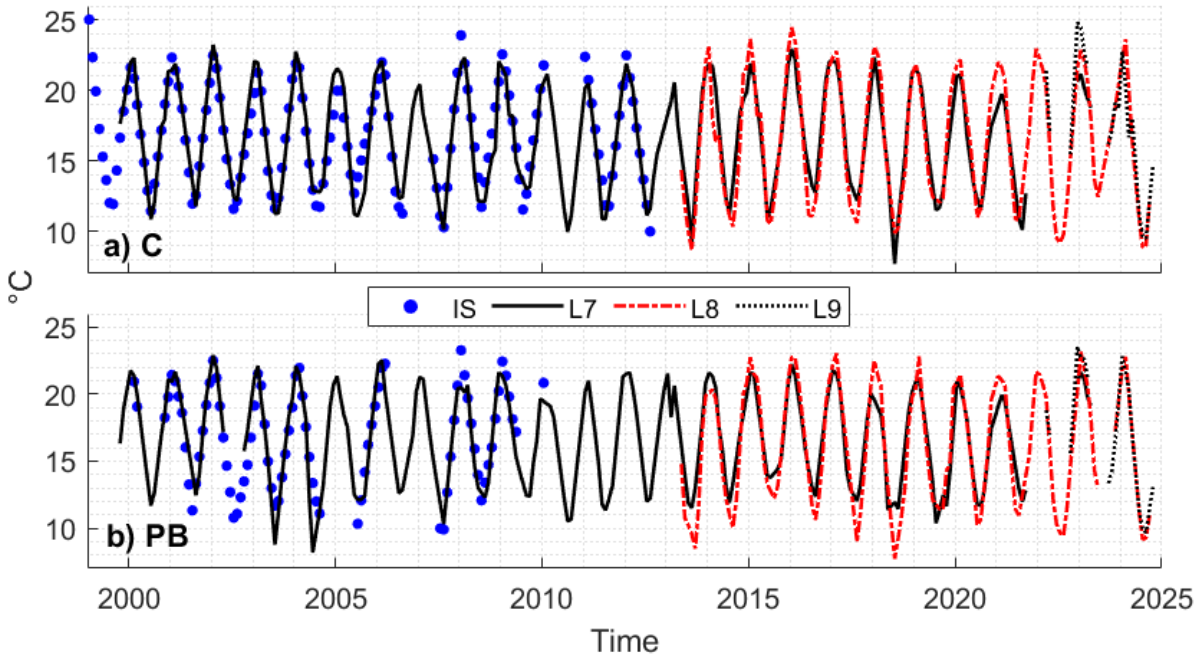


Figure III.3. Calibrated LSWT (°C) time series (L5, L7, L8, and L9) and in-situ (IS) series in Laguna Grande at the Centro station (C) and in Lake Lanalhue at the Playa Blanca station (PB) for the period 1998–2024.

Table III.4. Mean (μ) and standard deviation (σ) of the LSWT time series from in-situ (IS) and satellite data (L5, 7, 8, and 9). Average values at the sampling stations in Laguna Grande de San Pedro (LG) (stations: D, C, S) and Lake Lanalhue (LL) (stations: PP, FH, PB, SC, PM).

Series	Period	μ		σ	
		LG	LL	LG	LL
IS	1999-2012	16.69	16.69	3.42	3.59
L7		16.82	16.80	4.11	4.31
L7	2013-2024	16.78	16.39	4.05	3.95
L8		16.96	16.88	4.19	4.08
L8	2021-2024	17.75	17.48	4.33	4.47
L9		17.41	17.25	3.76	4.38

In Table III.4 there is a statistical comparison among in-situ and satellite datasets. For the overlapping periods between in-situ (IS) and satellite data, the coefficient of determination (R^2) consistently exceeded 0.87 in both LG and LL, indicating a strong correlation in temporal variability. Willmott's index of agreement (d) was also high (≥ 0.97), confirming the agreement in fluctuation patterns between datasets. RMSE values remained lower than 0.12, suggesting small differences in absolute LSWT values. P_{BIAS} was in all cases very close to zero, indicating high accuracy between datasets compared.

Table III.5. Pairs of series compared (in-situ (IS) and satellite: Landsat 7 (L7), 8 (L8) and 9 (L9)) using the statistical metrics: coefficient of determination (R^2, Eq. 1), root mean square error (RMSE, Eq. 2), Willmott's index of agreement (d, Eq. 3), and bias (Eq. 4). Average values at the sampling stations in Laguna Grande de San Pedro (D, C, S) and Lake Lanalhue (PP, FH, PB, SC, PM).

Serie	Período	$\boldsymbol{R^2}$		$NRMSE$		$\boldsymbol{d}$		P_{BIAS}	
		LG	LL	LG	LL	LG	LL	LG	LL
IS - L7	1999-2012	0.90	0.88	0.10	0.11	0.98	0.98	-0.01	-0.02
L7 - L8	2013-2023	0.87	0.88	0.10	0.11	0.97	0.97	0.004	-0.001
L8 - L9	2021-2024	0.89	0.91	0.12	0.11	0.99	0.99	-0.01	-0.04

4.2. Spatial and temporal analysis of LSWT

4.2.1. From LSWT model

The average annual climatology of the studied lakes (Figure III.4a and 4b) reveal that Lagoon Grande exhibits warmer mean annual surface water temperatures (≈16–18 °C) compared to Lake Lanalhue (≈15–16 °C). Seasonal climatologies (Figure III.4c–j) indicate clear thermal seasonality in both lakes, with autumn and spring showing intermediate temperatures (14-21 ºC), winter presenting the lowest values (≈9–13 °C), and summer reaching the highest (≈22–25 °C). Thermal gradients in the north-south direction within each lake are also evident, suggesting spatial heterogeneity possibly linked to morphology, depth, inflows and heat islands.

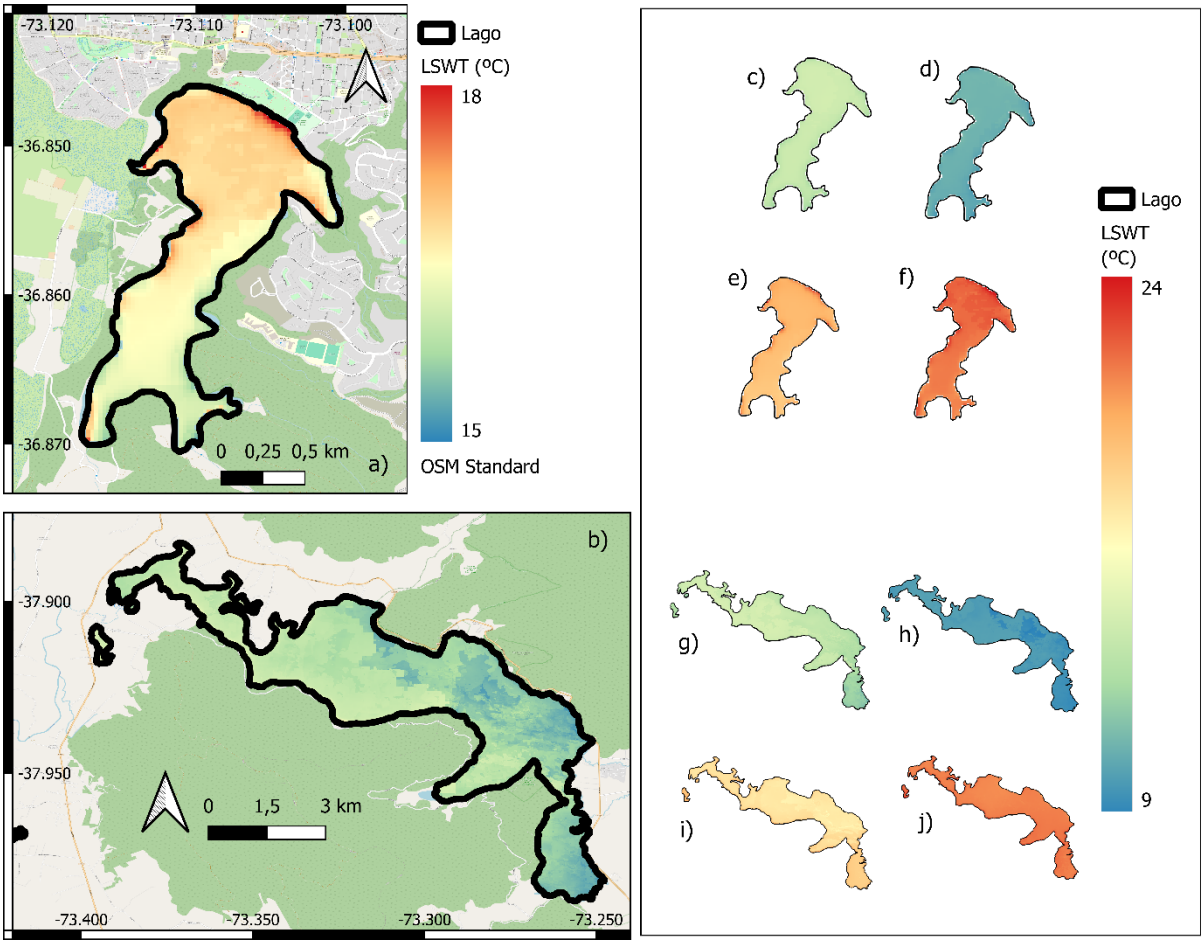


Figure III.4. On the left are the average annual climatology of a) Lagoon Grande de San Pedro and b) Lake Lanalhue. On the right are the seasonal climatologies of the same lakes in autumn (c and g), winter (d and h), spring (e and i), and summer (f and j). All climatologies were constructed from Landsat 8 (2013–2024) images calibrated with in-situ data (Section 3.2.1).

The monthly LSWT boxplot (Figure 5) shows the seasonality described. In Lagoon Grande (Figure III.5a), temperatures peak in austral summer (December, January, February (DJF)) (~22–25 °C) and reach their minimum in July (~10 °C) (winter). In Lake Lanalhue (Figure III.5b), maximum values also occur in summer (JF) (~22-23 °C) and minimum in August (~10 °C)

(winter). Now, in most cases, a ~2-3 °C of spatial variation of LSWT can be appreciated in Figure III.5a and 5b, indicating that in both lakes, temperature swing geographically by approximately 2 °C.

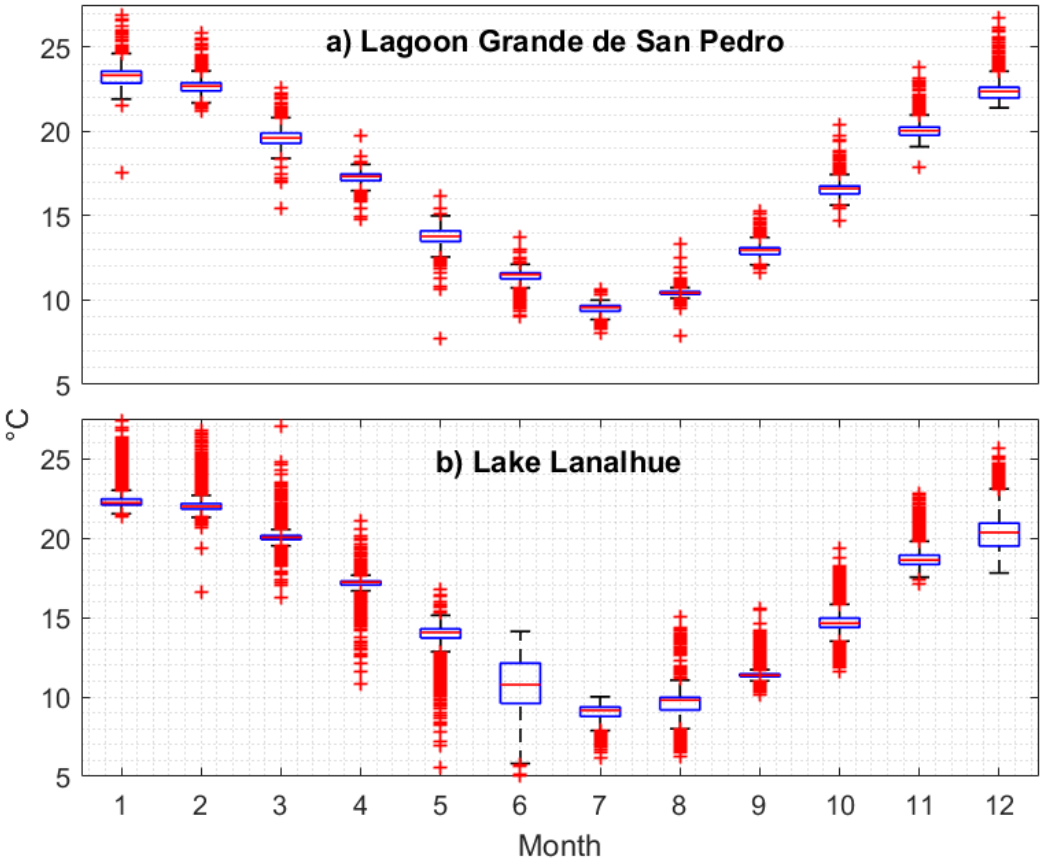


Figure III.5. Boxplot of monthly climatology of the LSWT at (a) Lagoon Grande de San Pedro and (b) Lake Lanalhue. Outliers in red. Period: 2013-2024.

4.2.2. From LSWT phenology

Figure III.6 presents the climatology of the monthly average domain of the LSWT for each Nahuelbutan lake during the period 2013–2024. A marked seasonality is evident across all lakes, with maximum temperatures during the summer months (DJF) and minimum in winter (June, July, August (JJA)), reaching extreme values around 26 °C and 7.5 °C, respectively. Despite this general seasonal coherence, there are differences in magnitudes of the LSWT climatologies among lakes. Some lakes exhibit higher temperatures in summer (e.g., LRed) or in winter (e.g., LG, LLl) whereas others remain among the coldest throughout the year (e.g., LAn, LQuid). Some lakes present higher thermic ranges (e.g., LLRed) while others show certain temperature stability (e.g., LCh, LQuil). These differences suggest spatial variability in thermal regimes, that could be influenced by factors such as morphology, altitude, hydrological connectivity, exposure to winds, hydrodynamic properties such as water renovation time, the degree of anthropogenic disturbance within the catchments and their locations. However, during the winter months (JJA), thermal differences among lakes tend to diminish, showing convergence toward the lowest annual values. This contrasts with the summer period, as LSWT differences become more pronounced.

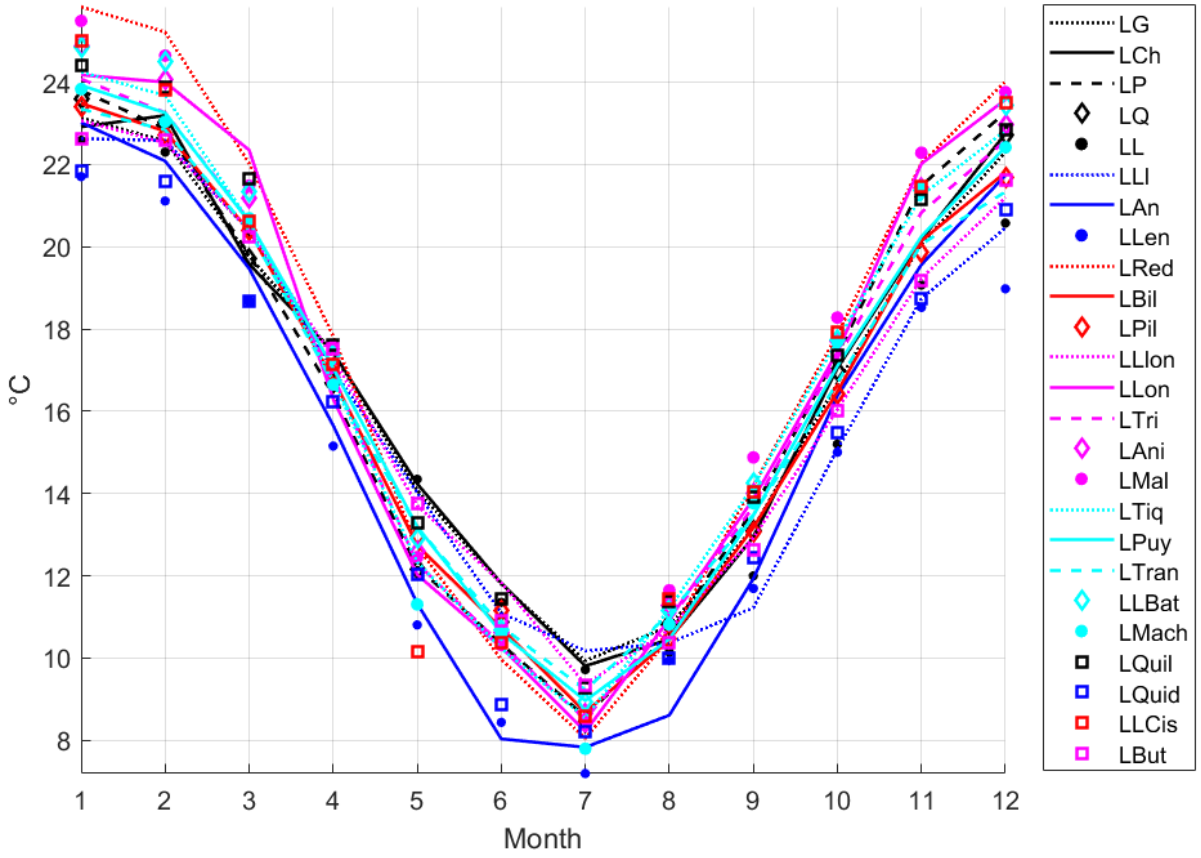


Figure III.6. Climatology of the monthly average domain of the LSWT in each Nahuelbutan Lake, based on satellite (Landsat 8) data. Period: 2013-2024.

Figure III.7 illustrates the average annual climatology of the Nahuelbutan Lakes in the period 2013-2024, based on Landsat 8 imagery. The map reveals clear latitudinal and altitudinal gradients in medium-sized lakes, such as Lagoons Grande and Chica (LG) de San Pedro (LCh) in the northern, at 4 m.a.s.l. (see Table III.4) regarding lakes Lanalhue an Lleulleu in the south at 12 m.a.s.l. Southern and higher-elevation lakes tend to be colder, while northern, lower-elevation lakes tend to be warmer. All the rest are small-sized lakes, and they show a diversity of thermal regimes without clear causality.

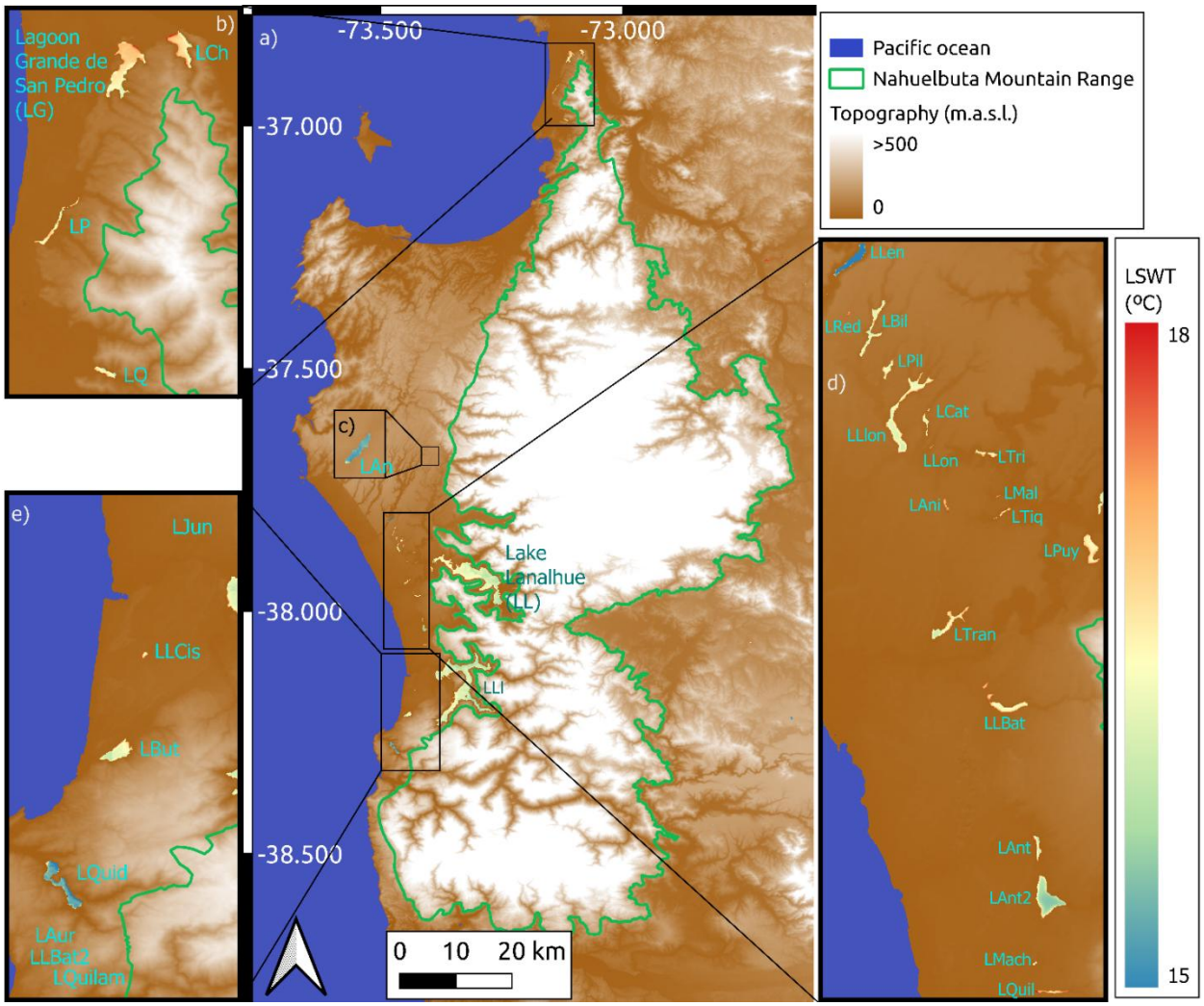


Figure III.7. Average annual climatology of the Nahuelbutan Lakes based on L8 satellite data. Period: 2013-2024. a) Study area. b) Zoom into northern Nahuelbutan lakes. c) Zoom into Lagoon Antihuala. d-e) Zoom into southern Nahuelbutan lakes.

5. Discussion

The results demonstrate that multi-sensor Landsat series, when calibrated with in-situ observations, can accurately reproduce both the temporal dynamics and the absolute values of LSWT in medium to small-sized lakes. The consistently high R^2 (≥0.87) and Willmott's index of agreement

(≥0.97) values indicate strong correspondence between satellite-derived and in-situ time series, while low *NRMSE* values (less than 0.12) and P_{BIAS} very close to zero confirm the possibility to rely on Landsat thermal bands for inland water monitoring and studying, by extending LSWT records over multi-decadal timescales.

One limitation in calibration stems from the temporal mismatch between datasets: in-situ measurements are collected at varying times of the day (09:00–18:00 local time), whereas Landsat overpasses occur consistently at 10:40 a.m. This difference could have introduced small but systematic discrepancies. However, because this study focuses on monthly and seasonal climatologies, those discrepancies would have negligible influence on the accuracy and representativeness of the resulting LSWT fields.

A key methodological decision was to base the final climatologies on Landsat 8 data (2013–2024) rather than Landsat 7, despite the latter's longer temporal coverage (since 1999). There is a 10-year period (2000–2013) that L8 does not cover, but L7 does, although with its widely known gaps. As a consequence, the LSWT data field on the surface of the lagoons was built using Landsat 8 files, which was an outstanding choice and produced great results. The next step, however, is to build the LSWT fields with Landsat 7 data (since 1999). The question then becomes: what happens if we interpolate the images to fill the spatial gaps present in the Landsat 7 files? How does the LSWT data fields result? Additionally, it would also be prudent to improve the

quality of the data fields by merging them with MODIS data. This approach could produce over two decades of monthly LSWT fields, greatly enhancing the capacity to study long-term thermal dynamics.

The spatial and seasonal climatologies derived from Landsat 8 reveal distinct patterns among the Nahuelbutan lakes. While all lakes share a coherent seasonal cycle—warmer in austral summer and cooler in winter—the magnitude and range of LSWT vary. Factors contributing to this spatial heterogeneity include lake morphology, altitude, hydrological connectivity, wind exposure, and catchment-level anthropogenic disturbance. Notably, these differences diminish during winter but become more pronounced during summer. Such variability should be considered when evaluating lake ecosystem processes, particularly under projected climate change scenarios.

The ability to construct high-resolution LSWT fields has direct ecological and management implications. In the studied region, eutrophication and harmful algal blooms (HABs) are pressing concerns, influenced by both nutrient inputs and water temperature. Long-term LSWT datasets can provide a first-order link between thermal regimes and ecological processes, particularly in lakes whose catchments have undergone significant land use changes, that in the study area includes mainly forestry, and then agriculture and urbanization. Water temperature is already part of the monitoring and management strategy for Chile's lake systems, but, as detailed in Appendix III.I, it is costly, and therefore very few Chilean lakes have effective and

historical monitoring of this parameter. In this context, the remote sensing tools presented here, together with the citizen water monitoring presented in Appendix III.I, could strengthen environmental management, contributing to the long-awaited modernization of the state.

From a technological perspective, this study underscores the value of open-access satellite archives and cloud-computing platforms such as Google Earth Engine (GEE). These tools enable low-cost, scalable environmental monitoring that can be enhanced by integrating LSWT with other remotely sensed water quality parameters (e.g., turbidity, chlorophyll-a) and hydromorphological metrics (e.g., lake level (Crétaux et al., 2016), surface area (Crétaux et al., 2011a)). SWOT and Copernicus LSTM missions will further expand capabilities, offering higher temporal resolution and global coverage of lake temperature and water levels.

In summary, the presented methodology is a reliable approach for reconstructing LSWT climatologies in medium to small-sized lakes where in-situ monitoring is limited or discontinuous. By extending these records temporally and integrating them with complementary datasets, future research can provide deeper insights into the thermal regimes of inland waters, their drivers, and their ecological consequences.

6. Conclusions

This study demonstrates that multi-sensor Landsat data, when calibrated with in-situ observations, can effectively reconstruct long-term lake surface water temperature (LSWT) records for medium to small-sized lakes. The methodology, implemented through the Google Earth Engine platform, provides a cost-effective and scalable approach to monitor inland water thermal regimes with high spatial resolution. The results reveal strong agreement between satellite-derived and in-situ data, with minimal bias and error, enabling the production of reliable seasonal and spatial climatologies.

Applied to the Nahuelbutan lakes, the approach highlighted clear thermal seasonality and spatial variability driven by morphological, hydrological, and climatic factors. These differences have important implications for lake ecology, particularly in regions facing eutrophication and harmful algal blooms. The generated LSWT datasets can support environmental management by linking thermal dynamics to ecological processes and human activities in the catchments.

The proposed methodology opens the door to retrieve other key parameters such as clorophyll-a or turbidity. It is transferable to other regions and can be enhanced by integrating additional satellite sources, such as Sentinel, MODIS, SWOT, and Copernicus LSTM, to extend temporal coverage and improve resolution. Such advances will strengthen our capacity to assess

long-term ecological changes, understand their drivers, and anticipate the ecological impacts of climate change on inland waters.

Appendix III.I: Monitoreo ciudadano de calidad del agua para su gestión en sistemas lacustres: Experiencia en Laguna Junquillar

Contexto

La integridad ecológica constituye un marco teórico para evaluar el estado o condición de un sistema socio-ecológico, integrando dimensiones ecológicas, físicas y sociales, entre otras. En el caso de los ecosistemas acuáticos, y particularmente desde una perspectiva física y de calidad del agua, este estado se representa a través de parámetros físico-químicos. Dichos parámetros permiten caracterizar el grado trófico de un lago, entendido como un indicador de su condición ecológica y de su trayectoria de envejecimiento natural. Según este enfoque, los lagos pueden clasificarse en distintas categorías tróficas, que en orden sucesivo serían: ultra-oligotróficos, oligotróficos, mesotróficos, eutróficos e hiper-eutróficos (Membrillo-Abad et al., 2016b). Como una alternativa diferente están los lagos distróficos ((Wakana et al., 2023).

En esta línea, se ha pensado durante mucho tiempo que los lagos en la medida que envejecen o se degradan, atravesarán la sucesión de grados tróficos mencionada, se convertirán en pantanos y luego en bosques (Long, 2017). Es su ciclo natural de envejecimiento. No obstante, esta simplificación ha sido cuestionada en los últimos años (Kornijów, 2023), al relevar la complejidad del comportamiento de los lagos cuyos grados tróficos responden a condiciones locales, donde se puede dar que un lago sea eutrófico muchos años, pero no por eso está degradado, sino que es su condición de base. Si bien existe este cuestionamiento, también existe una relación probada entre grado trófico, concentración de nutrientes y productividad. En la medida que un lago va atravesando los anteriores mencionados grados tróficos en orden (exceptuando el distrófico), van aumentando las concentraciones de nutrientes (principalmente fósforo y nitrógeno), turbidez y productividad (por lo tanto aumento en la clorofila-a) (Farnaz Nojavan et al., 2019). El problema es que este proceso toma miles de años y la especie humana lo ha acelerado a décadas (Parra et al., 2003).

En Chile, el desarrollo normativo ambiental en calidad del agua se inicia con la promulgación de la Ley 19.300, Sobre Bases Generales del Medio Ambiente y su Reglamento para la Dictación de Normas de Calidad Ambiental y de Emisión (Decreto Supremo 93/1995 MINSEGPRES (actualmente, DS 38/2012) (Galarce, 2020). La NSCA es necesaria para reconocer que un lago está contaminado. Luego, es posible implementar un plan de

descontaminación si el monitoreo arroja superación de umbrales máximos definidos por la norma. Para el levantamiento de la norma y el plan de descontaminación, un insumo clave es el estado trófico del lago. En Chile se están usando actualmente índices, como por ejemplo el de Carlson (1977), o el de Burns (2020), que se construyen en base a parámetros como: Profundidad del Disco Secchi (m), Fósforo superficial (mg/m³) y Clorofila superficial (mg/m³) (Urrutia et al., 2022).

En Chile, de los más 12.000 sistemas lacustres, actualmente sólo hay dos que cuentan con NSCA: Lago Villarrica y Lago Llanquihue. En contraste con los casos donde sí existe normativa y monitoreo sistemático, como en los lagos Villarrica y Llanquihue, hay otros cuerpos de agua relevantes que carecen de información oficial básica. Esta ausencia de datos no responde a la falta de relevancia ecológica del sistema, sino a limitaciones institucionales y presupuestarias, que restringen la cobertura de monitoreo a un número muy acotado de lagos en el país. Así, se evidencia la necesidad de fortalecer las capacidades técnicas y financieras del Estado para ampliar la red de vigilancia, condición indispensable para una gestión integrada de cuencas.

En el contexto de escasez de datos para la gestión ambiental, las herramientas de teledetección como la desarrollada en este capítulo juegan un rol. Pero, además, los datos ciudadanos, pueden volverse un fuerte aliado a la hora de extender el levantamiento de datos in-situ (San Llorente Capdevila et al., 2020). A continuación, se narra una experiencia exitosa de monitoreo

ciudadano del agua en el sistema humedal y laguna Junquillar, lo que abre puertas para incorporar el monitoreo ciudadano como un elemento clave en la gestión integrada de cuencas.

Experiencia de monitoreo ciudadano de calidad del agua en Laguna Junquillar.

Dentro del sistema de Lagos Nahuelbutanos, se encuentra el humedal y laguna Junquillar, ubicado en las faldas de la Cordillera de Nahuelbuta, insertado en el barrio de Lomas Coloradas, comuna de San Pedro de la Paz, región del Biobío, Chile.

El sistema natural y la comunidad humana tienen un vínculo antiguo asociado a la recreación, y sus habitantes relevan el lugar como espacio de conservación de flora y fauna nativa (Corporación Junquillar, 2024). Las principales causas de la contaminación en la Laguna Junquillar son la plantación forestal exótica, la urbanización y potencialmente la agricultura (Corporación Junquillar, 2024). En los últimos años, el sistema natural y el barrio aledaño se han visto fuertemente afectados por los recientes mega incendios forestales, el más destructivo en el verano de 2022-2023.

Ambientalmente, la urbanización suele estar vinculada a un proceso de degradación ambiental. No obstante, en el sistema Junquillar, la llegada de las personas promovió el resguardo de este espacio, movido por el sentido de

pertenencia y una relación simbiótica de protección hacia el humedal (Corporación Junquillar, 2024). La Corporación Junquillar nace de la agrupación de habitantes del lugar, con la intención de levantar información y llevar al sistema Junquillar a una protección efectiva, aplicando la Ley de Humedales Urbanos (Ley 21.202).

En este contexto la autora principal de esta tesis doctoral, junto a la Corporación Junquillar, dirigió un proyecto financiado por el Fondo Concursable de Vinculación con el Medio UdeC (FVCM), bajo el proyecto de código: VRIM2412, de nombre: “Programa de monitoreo comunitario del agua en Laguna Junquillar (San Pedro de la Paz)”. Este proyecto fue co-ejecutado para generar un sistema de monitoreo que apoye el proceso de protección ciudadana que viene dándose naturalmente en el territorio.

Operativamente, con el proyecto se adquirió el “Kit para Monitoreo de la Calidad del Agua - Alabama Water Quality - LAMOTTE” (Figure III.8), un laboratorio portátil de relativamente bajo costo que permite el monitoreo físico y químico del agua. Su implementación a nivel regional fue en el marco del proyecto Global Water Watch (GWW), del cuál surgió el manual: *Monitoreo comunitario del Agua, EL ENFOQUE DE GWW EN CUIDADO CO-PARTICIPATIVO DE CUENCAS*, el cual se utilizó como insumo para construir este documento.



Figure III.8. Kit para Monitoreo de la Calidad del Agua - Alabama Water Quality - LAMOTTE

Con esto, se logró generar participativamente junto a la Corporación Junquillar, un protocolo de monitoreo ciudadano de calidad del agua, para obtener seis parámetros fisicoquímicos de calidad del agua: temperatura, pH, dureza total, alcalinidad total, oxígeno disuelto y turbidez. En ese protocolo, y en base al conocimiento local, se sistematizaron puntos de muestreo en el cuerpo de agua pertinentes para responder a preguntas ambientales clave. Esto se sistematizó en un documento cuya portada se muestra en la Figure III.9 y que se puede ver completo en (Pedreros-Guarda, 2025).

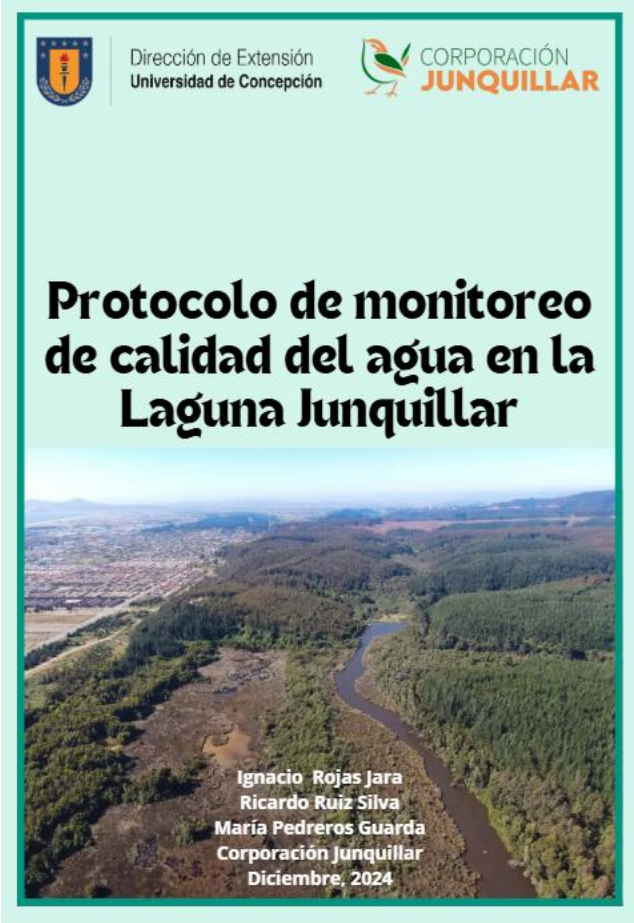


Figure III.9. Protocolo de monitoreo de calidad del agua en la Laguna Junquillar, co-generado junto a la Corporación Junquillar (Corporación Junquillar, 2025).

Datos ciudadanos en la gestión ambiental

La ciencia ciudadana, además de ser costo-efectiva, ofrece posibilidades únicas de incorporar a comunidades locales y actores clave en la gestión del agua y la toma de decisiones (Metcalfe et al., 2022). Esta experiencia de monitoreo levantada en este anexo representa un caso donde

se logró diseñar e implementar un sistema de monitoreo ciudadano en un cuerpo de agua con un alto valor socio-ecológico relevado por la misma comunidad aledaña. Esto se enmarca en un trabajo permanente por parte de la Corporación Junquillar para el resguardo del sistema Junquillar, tanto en el proceso de declaración como humedal urbano, educación ambiental, restauración y aporte en el fortalecimiento del tejido social. Este trabajo continuo le otorga al sistema de monitoreo sostenibilidad en el tiempo, y datos que pueden ser integrados con distintos fines.

Si bien, en general, hay ciertas dificultades para que los datos ciudadanos sean integrados en la gestión pública, debido a dudas en la precisión, exactitud y confiabilidad de los métodos utilizados, se pueden seguir ciertas directrices para sobreponerse a esto (Warner et al., 2024), y existen algunos ejemplos reportados donde ya ha ocurrido. Tal es el caso presentado por Woods (2025): mediante kits y monitoreo local, datos ciudadanos recolectados lagos y ríos del Reino Unido han sido utilizados para fiscalización ambiental.

Para que esta integración sea posible, el modelo de gestión del agua es un aspecto importante. Un ejemplo de modelo avanzado de gestión agua en Latinoamérica es el de Brasil, donde existe un sistema de comités de cuenca hidrográfica y agencias de cuenca, inspirado en el modelo francés de gestión integrada del recurso hídrico (Agência Nacional de Águas, 2010). Este enfoque descentralizado y participativo busca que la toma de decisiones sobre

el agua ocurra a nivel de cuenca, integrando a actores locales, usuarios, sociedad civil y Estado.

Todo lo anterior expuesto en este apartado y en este capítulo da cuenta de la posibilidad real de avanzar hacia modelos de gestión que integren herramientas de teledetección y participación ciudadana para poder cuidar todos los ecosistemas para los cuales el presupuesto nacional no alcanza. En el caso de Chile, la NSCA de calidad ambiental podría ser generada y los cuerpos de agua fiscalizados si contáramos con más infraestructura de monitoreo como lo que aquí se propone.

Revisitando las principales recomendaciones que nacen del Capítulo II para permitir la restauración socio-ecológica, la posibilidad de ampliar las capacidades de fiscalización permitiría aportar enormemente al punto: “detener las causas de la degradación”. Al superarse la norma, se puede implementar un plan de descontaminación y medidas de control de las causas de la degradación de las cuencas.

Referencias

Abarca-Del-Rio, R., CrÉtaux, J.-F., Berge-Nguyen, M., & Maisongrande, P. (2012). Does Lake Titicaca still control the Lake Poopó system water levels? An investigation using satellite altimetry and MODIS data (2000–2009). *Remote Sensing Letters*, *3*(8), 707-714. https://doi.org/10.1080/01431161.2012.667884

Abarzúa et al. (2020). *Informe final: Análisis de Testigo Sedimentari... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Informe%20final%3A%20An%C3%A1lisis%20de%20Testigo%20Sedimentario%20en%20Lago%20Lanal

hue%2C%20Provincia%20de%20Arauco%2C%20Regi%C3%B3n%20del%20Biob%C3%ADo&author=A.M.%20Abarz%C3%BAa&publication_year=2020
Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, *5*(1), 170191. https://doi.org/10.1038/sdata.2017.191
Abubakar, H. B. (2024). *Evaluation of high-resolution precipitation datasets CHIRPS, TerraClimate and TAMSAT over the Enkangala Escarpment of South Africa*. Research Square. https://doi.org/10.21203/rs.3.rs-4365508/v1
Adjovu, G. E., Stephen, H., James, D., & Ahmad, S. (2023). Overview of the Application of Remote Sensing in Effective Monitoring of Water Quality Parameters. *Remote Sensing*, *15*(7), 1938. https://doi.org/10.3390/rs15071938
Afsharian, S., & Taylor, P. A. (2019). On the Potential Impact of Lake Erie Wind Farms on Water Temperatures and Mixed-Layer Depths: Some Preliminary 1-D Modeling Using COHERENS. *Journal of Geophysical Research: Oceans*, *124*(3), 1736-1749. https://doi.org/10.1029/2018JC014577
Agência Nacional de Águas. (2010). *NORMAS DE COBRANÇA PELO USO DE RECURSOS HÍDRICOS*. https://www.ana.gov.br/arquivos/institucional/sge/CEDOC/Catalogo/2010/NormasDeCobrancaPeloUsoDosRecursosHidricos2010.pdf
Agência Nacional de Águas e Saneamento Básico (ANA). (2025). *Qualidade da água*. https://www.gov.br/ana/pt-br/assuntos/monitoramento-e-eventos-criticos/qualidade-da-agua/qualidade-da-agua
Aguayo Arias, M. I. (2008). *El cambio de uso del suelo en el centro sur de Chile. Comprendiendo su dinámica a través de la modelación espacialmente explícita y explorando sus efectos ambientales en una cuenca hidrológica de meso escala.* [[PhD Thesis], Universidad de Concepción]. https://repositorio.udec.cl/handle/11594/6004
Aguayo, M., Pauchard, A., Azócar, G., & Parra, O. (2009). Cambio del uso del suelo en el centro sur de Chile a fines del siglo XX: Entendiendo la dinámica espacial y temporal del paisaje. *Revista chilena de historia natural*, *82*(3), 361-374.
Alaniz, A. J., Abarzúa, A. M., Martel-Cea, A., Jarpa, L., Hernández, M., Aquino-López, M. A., & Smith-Ramírez, C. (2021). Linking sedimentological and spatial analysis to assess the impact of the forestry industry on soil loss: The case of Lanalhue Basin, Chile. *CATENA*, *207*, 105660. https://doi.org/10.1016/j.catena.2021.105660
Alaniz, A. J., Smith-Ramírez, C., Rendón-Funes, A., Hidalgo-Corrotea, C., Carvajal, M. A., Vergara, P. M., & Fuentes, N. (2022). Multiscale spatial analysis of headwater vulnerability in South-Central Chile reveals a high threat due to deforestation and climate change. *Science of The Total Environment*, *849*, 157930. https://www.sciencedirect.com/science/article/pii/S004896972205029X
Albus, K. H., Thompson, R., Mitchell, F., Kennedy, J., & Ponette-González, A. G. (2020). Accuracy of long-term volunteer water monitoring data: A multiscale analysis from a statewide citizen science program. *PLOS ONE*, *15*(1), e0227540. https://doi.org/10.1371/journal.pone.0227540
Alfonso, L., Gharesifard, M., & Wehn, U. (2022). Analysing the value of environmental citizen-generated data: Complementarity and cost per observation. *Journal of*

Environmental Management, *303*, 114157. https://doi.org/10.1016/j.jenvman.2021.114157

Allan, M. G., Hamilton, D. P., Trolle, D., Muraoka, K., & McBride, C. (2016). Spatial heterogeneity in geothermally-influenced lakes derived from atmospherically corrected Landsat thermal imagery and three-dimensional hydrodynamic modelling. *International Journal of Applied Earth Observation and Geoinformation*, *50*, 106-116. https://doi.org/10.1016/j.jag.2016.03.006

Almanza, V., Parra, O., De M. Bicudo, C. E., Baeza, C., Beltran, J., Figueroa, R., & Urrutia, R. (2016). Occurrence of toxic blooms of Microcystis aeruginosa in a central Chilean (36° Lat. S) urban lake. *Revista Chilena de Historia Natural*, *89*(1), 8. https://doi.org/10.1186/s40693-016-0057-7

Altieri, M. A., & Rojas, A. (1999). Ecological Impacts of Chile's Neoliberal Policies, with Special Emphasis on Agroecosystems. *Environment, Development and Sustainability*, *1*(1), 55-72.

Altman, D. G. (1990). *Practical Statistics for Medical Research*. Chapman and Hall/CRC. https://doi.org/10.1201/9780429258589

Alvial Vásquez, F.-J., Abarca-del-Río, R., & Ávila, A. I. (2020). High-Resolution Precipitation Gridded Dataset on the South-Central Zone (34° S–41° S) of Chile. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.519975

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M., Moghaddam, S. H. A., Mahdavi, S., Ghahremanloo, M., Parsian, S., Wu, Q., & Brisco, B. (2020). Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 5326-5350. https://doi.org/10.1109/JSTARS.2020.3021052

Amour, I., & Kauranne, T. (2017). A variational ensemble Kalman filtering method for data assimilation using 2D and 3D version of COHERENS model. *International Journal for Numerical Methods in Fluids*, *83*(6), 544-558. https://doi.org/10.1002/fld.4276

Angrosino, M. (2012). *Etnografía y observación participante en Investigación Cualitativa*. Ediciones Morata.

Araos, F., Catalán, E., Nuñez, D., Riquelme, W., Cortinez, V., de Fina, D., & Anbleyth-Evans, J. (2023). Cuidando la Patagonia Azul: Prácticas y estrategias de los pueblos originarios para curar las zonas marinas del sur de Chile. *The Journal of Latin American and Caribbean Anthropology*, *28*(4), 286-297. https://onlinelibrary.wiley.com/doi/abs/10.1111/jlca.12695

Araya. (2019). *Desafíos del turismo y la conservación de la biodiversidad* (Primera edición, septiembre de 2019). Amukan Editorial itinerante.

Ardiantiono, Deere, N. J., Seaman, D. J. I., Mamat Rahmat, U., Ramadiyanta, E., Lubis, M. I., Trihangga, A., Yasin, A., Alza, G., Sari, D. P., Daud, M., Abdullah, R., Mutia, R., Melvern, D., Tarmizi, Supriatna, J., & Struebig, M. J. (2025). Improved cost-effectiveness of species monitoring programs through data integration. *Current Biology*, *35*(2), 391-397.e3. https://doi.org/10.1016/j.cub.2024.11.051

Argyilan, E. P., & Forman, S. L. (2003). Lake Level Response to Seasonal Climatic Variability in the Lake Michigan-Huron System from 1920 to 1995. *Journal of Great Lakes Research*, *29*(3), 488-500. https://doi.org/10.1016/S0380-1330(03)70453-5

Aróstegui, M. G. (2001). Cultura de la resistencia. Concepciones teóricas y metodológicas para su estudio. *Islas*, (127), 20-41. http://islas.uclv.edu.cu/index.php/islas/article/download/721/646

Arroyo, M. T. K. (2006). *El hotspot chileno, prioridad mundial para la conservación. Diversidad de ecosistemas, ecosistemas terrestres*.

Arsen, A., Crétaux, J.-F., Berge-Nguyen, M., & Del Rio, R. A. (2014). Remote Sensing-Derived Bathymetry of Lake Poopó. *Remote Sensing*, *6*(1), 407-420. https://doi.org/10.3390/rs6010407

Ascencio, E., Rivera, P., Cruces, F., Vila, I., Ascencio, E., Rivera, P., Cruces, F., & Vila, I. (2018). Estudio morfológico de Naiadinium polonicum (Dinophyceae) reportado por primera vez en aguas continentales de Chile. *Gayana. Botánica*, *75*(1), 438-446. https://doi.org/10.4067/S0717-66432018000100438

Assumpção, T. H., Popescu, I., Jonoski, A., & Solomatine, D. P. (2018). Citizen observations contributing to flood modelling: Opportunities and challenges. *Hydrology and Earth System Sciences*, *22*(2), 1473-1489. https://doi.org/10.5194/hess-22-1473-2018

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., Van Den Hurk, B., Hirschi, M., & Betts, A. K. (2009). A Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System. *Journal of Hydrometeorology*, *10*(3), 623-643. https://doi.org/10.1175/2008JHM1068.1

Banco Central de Chile. (2025). *Base de Datos Estadísticos (BDE)*. https://si3.bcentral.cl/siete/ES/Siete/Cuadro/CAP_CCNN/MN_CCNN76/CCNN_EP18_05_ratio

Baracchini, T., Hummel, S., Verlaan, M., Cimatoribus, A., Wüest, A., & Bouffard, D. (2020). An automated calibration framework and open source tools for 3D lake hydrodynamic models. *Environmental Modelling & Software*, *134*, 104787. https://doi.org/10.1016/j.envsoft.2020.104787

Barría, P., Chadwick, C., Ocampo-Melgar, A., Galleguillos, M., Garreaud, R., Díaz-Vasconcellos, R., Poblete, D., Rubio-Álvarez, E., & Poblete-Caballero, D. (2021). Water management or megadrought: What caused the Chilean Aculeo Lake drying? *Regional Environmental Change*, *21*(1), 19. https://doi.org/10.1007/s10113-021-01750-w

Barros Delgado, B. B. J. (2022). *Dinámica de los asentamientos rurales y su relación con la expansión forestal en las comunas de Curanilahue, Lebu y Los Álamos, entre el periodo 1960—2002*. https://repositorio.uchile.cl/handle/2250/188639

Batina, A., & Krtalić, A. (2024). Integrating Remote Sensing Methods for Monitoring Lake Water Quality: A Comprehensive Review. *Hydrology*, *11*(7), 92. https://doi.org/10.3390/hydrology11070092

BCN. (2024). *Biblioteca del Congreso Nacional de Chile. Glosario de términos geográficos*. https://www.bcn.cl/siit/glosario/index_html

BCNa. (2024). *Reporte Comunal—Biblioteca del Congreso Nacional de Chile*. https://www.bcn.cl/siit/reportescomunales/comunas_v.html?anno=2023&idcom=8108

BCNb. (2017). *Buscador Estadístico—SIIT*. https://www.bcn.cl/siit/estadisticasterritoriales//resultados-consulta?id=326233

BCNc. (2024). *Chile: Población censada y tasas de crecimiento medio anual, según ciudades, 1950-2002*. https://www.memoriachilena.gob.cl/602/w3-article-74944.html

Beguería, S., Vicente Serrano, S. M., Reig-Gracia, F., & Latorre Garcés, B. (2023). *SPEIbase v.2.9 [Dataset]* [Dataset]. DIGITAL.CSIC. https://doi.org/10.20350/digitalCSIC/15470

Belete, M. D., Diekkrüger, B., & Roehrig, J. (2017). Linkage between Water Level Dynamics and Climate Variability: The Case of Lake Hawassa Hydrology and ENSO Phenomena. *Climate*, *5*(1), 21. https://doi.org/10.3390/cli5010021

Bengoa, J. (2000). *Historia del pueblo mapuche: (Siglo XIX y XX)*. Lom Ediciones.

Bengtsson, L. (2012). Water Balance of Lakes. En L. Bengtsson, R. W. Herschy, & R. W. Fairbridge (Eds.), *Encyclopedia of Lakes and Reservoirs* (pp. 863-864). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4410-6_18

Betts, A. K., Reid, D., & Crossett, C. (2020). Evaluation of the FLake Model in ERA5 for Lake Champlain. *Frontiers in Environmental Science*, *8*. https://doi.org/10.3389/fenvs.2020.609254

Beutel, M. W., Horne, A. J., Roth, J. C., & Barratt, N. J. (2001). Limnological effects of anthropogenic desiccation of a large, saline lake, Walker Lake, Nevada. *Hydrobiologia*, *466*(1), 91-105. https://doi.org/10.1023/A:1014569521381

Biblioteca del Congreso Nacional. (2021, octubre 13). *Biblioteca del Congreso Nacional | Ley Chile*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Biblioteca del Congreso Nacional. (2023, septiembre 6). *Ley 21600 CREA EL SERVICIO DE BIODIVERSIDAD Y ÁREAS PROTEGIDAS Y EL SISTEMA NACIONAL DE ÁREAS PROTEGIDAS*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Bio Bio (Director). (2023, febrero 13). *Dichos de Boric por regulación de industria forestal fueron catalogados como «fuera de contexto»* [Video recording]. https://www.youtube.com/watch?v=do0zHOXR5Us

Bolados, P., Espinoza, L., & Panez, A. (2024). Una aproximación decolonial a las Zonas de Sacrificio en Chile. *Vibrant: Virtual Brazilian Anthropology*, *21*, e21603. https://www.scielo.br/j/vb/a/vtQ6tPk9TWjThNfhNJTLtcv/?lang=es

Bongioannini Cerlini, P., Saraceni, M., Silvestri, L., Meniconi, S., & Brunone, B. (2022). Monitoring the Water Mass Balance Variability of Small Shallow Lakes by an ERA5-Land Reanalysis and Water Level Measurement-Based Model. An Application to the Trasimeno Lake, Italy. *Atmosphere*, *13*(6), Article 6. https://doi.org/10.3390/atmos13060949

Bonney, P. R., Hansen, B. D., & Baldwin, C. (2023). Citizen Science and Natural Resource Management: A Social Network Analysis of Two Community-Based Water Monitoring Programs. *Society & Natural Resources*, *36*(6), 600-621. https://doi.org/10.1080/08941920.2023.2183445

Boy, F., Crétaux, J.-F., Boussaroque, M., & Tison, C. (2022). Improving Sentinel-3 SAR Mode Processing Over Lake Using Numerical Simulations. *IEEE Transactions on Geoscience and Remote Sensing*, *60*, 1-18. https://doi.org/10.1109/TGRS.2021.3137034

Bravo Ferretti, C., Sandoval-Díaz, J., Astudillo Pizarro, F., Bravo Ferretti, C., Sandoval-Díaz, J., & Astudillo Pizarro, F. (2022). Narrativas del acorralamiento. Identidad de Lugar en la Bahía de Coronel a partir de la reconversión productiva. *Revista de historia (Concepción)*, *29*(1), 73-105.

http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-88322022000100073&lng=es&nrm=iso&tlng=en

Bravo Orrego, C. M. (2018). *Caracterización de la precipitación en la Cordillera de Nahuelbuta según la microfísica bajo la cual ocurre* [[PhD Thesis], Universidad de Chile]. https://repositorio.uchile.cl/handle/2250/168171

Brown, C. F., Brumby, S. P., Guzder-Williams, B., Birch, T., Hyde, S. B., Mazzariello, J., Czerwinski, W., Pasquarella, V. J., Haertel, R., Ilyushchenko, S., Schwehr, K., Weisse, M., Stolle, F., Hanson, C., Guinan, O., Moore, R., & Tait, A. M. (2022). Dynamic World, Near real-time global 10 m land use land cover mapping. *Scientific Data*, *9*(1), 251. https://www.nature.com/articles/s41597-022-01307-4

Budds, J. (2013). Water, Power, and the Production of Neoliberalism in Chile, 1973–2005. *Environment and Planning D: Society and Space*, *31*(2), 301-318. https://doi.org/10.1068/d9511

Burić, D., & Penjišević, I. (2023). Southern Hemisphere temperature trend in association with greenhouse gases, El Niño Southern Oscillation, and Antarctic Oscillation. *Időjárás*, *127*(1), 23-42. https://doi.org/10.28974/idojaras.2023.1.2

Burns, N. (2020). *Protocol for Monitoring Trophic Levels of New Zealand Lakes and Reservoirs*.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, *2*. https://www.frontiersin.org/articles/10.3389/feart.2014.00026

Carlson, R. E. (1977). A trophic state index for lakes. *Limnology and Oceanography*, *22*(2), 361-369. https://doi.org/10.4319/lo.1977.22.2.0361

Carmona, A., & Nahuelhual, L. (2012). Combining land transitions and trajectories in assessing forest cover change. *Applied Geography*, *32*(2), 904-915. https://www.sciencedirect.com/science/article/pii/S0143622811001755

Caro, C. S. M. (2003). *Aproximación a las estrategias de sobrevivencia de las familias de la caleta de Boca Sur Viejo en San Pedro de la Paz; experiencia y estudio de caso* [[PhD Thesis]]. Universidad de Concepción.

Carrasco Henríquez, N., & Mendoza Leal, C. (2021). Restoration as a re-commoning process. Territorial initiative and global conditions in the process of water recovery in the 'Cordillera de Nahuelbuta', Chile. *Ecosystems and People*, *17*(1), 556-573. https://doi.org/10.1080/26395916.2021.1993345

Castillo, S. F. (s. f.). *Ciudad y el derecho al buen vivir: Contribución rural a la reconstrucción de espacios fragmentados Barrio Boca Sur, Concepción, Chile.*

Chazdon, R. L., Falk, D. A., Banin, L. F., Wagner, M., J. Wilson, S., Grabowski, R. C., & Suding, K. N. (2024). The intervention continuum in restoration ecology: Rethinking the active–passive dichotomy. *Restoration Ecology*, *32*(8), e13535. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.13535

Cheng, C., Du, W., Li, J., Bao, A., Ge, W., Wang, S., Ma, D., & Pan, Y. (2023). Spatiotemporal Variations of Glacier Mass Balance in the Tomur Peak Region

Based on Multi-Source Altimetry Remote Sensing Data. *Remote Sensing*, *15*(17), 4143. https://doi.org/10.3390/rs15174143

Cheng, C., Xing, Z., Ye, L., Yang, J., & Xie, Z. (2024). Characteristics and Influencing Factors of Landscape Pattern Gradient Transformation of Small-Scale Agroforestry Patches in Mountain Cities. *Sustainability*, *16*(15), 6322. https://doi.org/10.3390/su16156322

Chicco, D., Warrens, M. J., & Jurman, G. (2021). The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Computer Science*, *7*, e623. https://doi.org/10.7717/peerj-cs.623

Chile_ING_ESP.xls. (s. f.). Recuperado 25 de julio de 2025, de https://www.memoriachilena.gob.cl/archivos2/pdfs/MC0018840.PDF

Choongik, C. (2025). Unequal Distribution of Climate Change Impacts across Regions: Towards Climate Justice. *Journal of Distribution Science*, *23*(4), 103-116. https://koreascience.kr/article/JAKO202512250404430.page

Choukrani, H., Lacombe, G., Zwarteveen, M., Kuper, M., Taky, A., & Hammani, A. (2023). Sense-making and shaping of temporary wetlands: A socio-hydrological analysis of dichotomous ontologies of merjas in Morocco. *Journal of Hydrology*, 130434. https://doi.org/10.1016/j.jhydrol.2023.130434

Clark, B., & York, R. (2008). Rifts and Shifts: Getting to the Root of Environmental Crises. *Monthly Review*, *60*(6), 13. http://archive.monthlyreview.org/index.php/mr/article/view/MR-060-06-2008-10_2

Clark, N. E., Eber, L. E., Laurs, R. M., Renneer, J. A., & Saur, J. F. T. (1974). *Heat exchange between ocean and atmosphere in the eastern North Pacific for 1961-71*. https://repository.library.noaa.gov/view/noaa/11864/noaa_11864_DS1.pdf

Clark, & York. (2005). Carbon metabolism: Global capitalism, climate change, and the biospheric rift. *Theory and Society*, *34*(4), 391-428. https://doi.org/10.1007/s11186-005-1993-4

CNES. (2015). *How altimetry works [online]. Toulouse, Centre national d'études spatiales (CNES)*. https://cnes.fr/en/how-altimetry-works

Comisión Presidencial para la Paz y el Entendimiento. (2025). *Resumen ejecutivo de las recomendaciones al Estado de Chile en materia de tierras y derechos del pueblo Mapuche*. Ministerio Secretaría General de la Presidencia. https://www.comisionpazyentendimiento.gob.cl/wp-content/uploads/2025/05/Resumen-Ejecutivo-Oficial-Cierre-Comision-para-la-Paz-y-el-Entendimiento.pdf

Condom, T., Martínez, R., Pabón, J. D., Costa, F., Pineda, L., Nieto, J. J., López, F., & Villacis, M. (2020). Climatological and Hydrological Observations for the South American Andes: In situ Stations, Satellite, and Reanalysis Data Sets. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.00092

Congalton, R. G., Gu, J., Yadav, K., Thenkabail, P., & Ozdogan, M. (2014). Global Land Cover Mapping: A Review and Uncertainty Analysis. *Remote Sensing*, *6*(12), 12070-12093. https://doi.org/10.3390/rs61212070

COPERNICUS. (2025). *Land Monitoring Service: Temperature and Reflectance*. https://land.copernicus.eu/en/products/temperature-and-reflectance

Corporación Junquillar. (2024). *Protocolo de monitoreo de calidad del agua en la Laguna Junquillar*.

Corporación Junquillar. (2025). *Laguna Junquillar (@lagunajunquillar) • Fotos y videos de Instagram*. https://www.instagram.com/lagunajunquillar/

Correa, M. (2021). La Historia del Despojo; El Origen de la Propiedad Particular en el Territorio. *Santiago, Chile: Ceibo-Pehuén Ediciones*.

Cosgrove, A., & Berkelhammer, M. (2018). Downwind footprint of an urban heat island on air and lake temperatures. *Npj Climate and Atmospheric Science*, *1*(1), 46. https://doi.org/10.1038/s41612-018-0055-3

(CR)2. (2025). *Explorador climático (CR)2* (Available online) [Dataset]. https://explorador.cr2.cl/

Cretaux, J., Kouraev, A., Papa, F., Bergé-Nguyen, M., Cazenave, A., Aladin, N., & Plotnikov, I. (2005). *Water balance of the Big Aral Sea from satellite remote sensing and in situ observations*. *31*.

Crétaux, J.-F., Abarca-del-Río, R., Bergé-Nguyen, M., Arsen, A., Drolon, V., Clos, G., & Maisongrande, P. (2016). Lake Volume Monitoring from Space. *Surveys in Geophysics*, *37*(2), 269-305. https://doi.org/10.1007/s10712-016-9362-6

Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011a). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011b). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., & Birkett, C. (2006). Lake studies from satellite radar altimetry. *Comptes Rendus Geoscience, La Terre observée depuis l'espace*, *338*(14), 1098-1112. https://doi.org/10.1016/j.crte.2006.08.002

CTOH. (2024, julio 10). *Altimetric Time Series Software (AlTiS) [software]*. GitLab. https://gitlab.com/ctoh/altis

Cuomo, C. J. (2011). Climate change, vulnerability, and responsibility. *Hypatia*, *26*(4), 690-714.

Da Silva, J. S., Seyler, F., Calmant, S., Rotunno Filho, O. C., Roux, E., Araújo, A. A. M., & Guyot, J. L. (2012). Water level dynamics of Amazon wetlands at the watershed scale by satellite altimetry. *International Journal of Remote Sensing*, *33*(11), 3323-3353. https://doi.org/10.1080/01431161.2010.531914

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018a). Understanding the abrupt climate change in the mid-1970s from a phase-space transform perspective. *Journal of Applied Meteorology and Climatology*, *57*(11), 2551-2560. https://journals.ametsoc.org/view/journals/apme/57/11/jamc-d-17-0345.1.xml

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018b). *Understanding the Abrupt Climate Change in the Mid-1970s from a Phase-Space Transform Perspective*. https://doi.org/10.1175/JAMC-D-17-0345.1

Davidson, N. C., Fluet-Chouinard, E., & Finlayson, C. M. (2018). Global extent and distribution of wetlands: Trends and issues. *Marine and Freshwater Research*, *69*(4), 620-627. https://www.publish.csiro.au/mf/MF17019

Delgado, F., & Rist. (2016). *Las ciencias desde la perspectiva del diálogo de saberes, la transdisciplinariedad y el diálogo intercientífico*.

Deltares. (2025). *Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments User Manual Hydro-Morphodynamics Version: 4.05.* https://www.google.com/search?q=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&oq=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBBzQxOWowajSoAgCwAgE&sourceid=chrome&ie=UTF-8

DGA. (2025a). *Red hidrométrica en línea DGA.* [Dataset]. https://dga.mop.gob.cl/servicioshidrometeorologicos/Paginas/default.aspx

DGA. (2025b). *Sistema Hidrométrico en Línea | Dirección General de Aguas*. https://dga.mop.gob.cl/sistema-hidrometrico-en-linea/

Di Chiro, G. (2015). A New Spelling Of Sustainability: Engaging Feminist-Environmental Justice Theory And Practice. *Practising Feminist Political Ecologies: Moving Beyond The «Green Economy»*, 211-236. https://doi.org/10.5040/9781350221970.ch-007

Echeverría, C., Bolados, G., Rodriguez, J., Aguayo, M., & Premoli, A. (s. f.). Ecología de Paisajes Forestales. *2014*.

ECMWF. (2020). *ECMWF Confluence Wiki: 3.3. OpenIFS: Surface Model HTESSEL [online]. Reading, European Centre for Medium-Range Weather Forecasts (ECMWF).* https://confluence.ecmwf.int/display/OIFS/3.3+OpenIFS%3A+Surface+Model+HTESSEL

ECMWF. (2025). *ERA5: Data documentation—Copernicus Knowledge Base—ECMWF Confluence Wiki*. https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation

ECMWF/C3S. (2024a). *Earth Engine Data Catalog: ERA5 Monthly Aggregates [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#bands

ECMWF/C3S. (2024b). *Earth Engine Data Catalog: ERA5-Land Monthly Aggregated [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR

ECOMOD. (2025). *COHERENS modelling system. ECOMOD – Marine Ecosystem Modelling*. https://ecomod.be/projects/COHERENS/

EEDC. (2025a). *USGS Landsat 8 Level 2, Collection 2, Tier 1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

EEDC. (2025b). *WorldClim Climatology V1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/WORLDCLIM_V1_MONTHLY?hl=es-419

EEDCa. (2025). *USGS Landsat 8 Collection 2 Tier 1 and Real-Time data Raw Scenes* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_RT?hl=es-419

EEDCb. (2025). *USGS Landsat 8 Collection 2 Tier 1 TOA Reflectanc* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_TOA?hl=es-419

EEDCc. (2025). *USGS Landsat 8 Level 2, Collection 2, Tier 1* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

Elachi, C., & Van Zyl, J. J. (2006). Introduction to the physics and techniques of remote sensing. John Wiley and Sons. *New Jersey. USA 513p*.

Elachi, C., & Zyl, J. J. van. (2021). *Introduction to the Physics and Techniques of Remote Sensing*. John Wiley & Sons.

EMOL, E. M. (2023, febrero 13). *Monsalve y debate abierto por Boric sobre industria forestal: «Sería irracional que la sociedad no diera una discusión»*. Emol. https://www.emol.com/noticias/Nacional/2023/02/13/1086588/monsalve-industria-forestal.html

EROS. (2022, noviembre 9). *USGS EROS Archive—Landsat Archives—Landsat 8-9 OLI/TIRS Collection 2 Level-2 Science Products | U.S. Geological Survey*. https://www.usgs.gov/centers/eros/science/usgs-eros-archive-landsat-archives-landsat-8-9-olitirs-collection-2-level-2

ESA. (2025a). *ATSR Reprocessing for Climate: Lake Surface Water Temperature & Ice Cover (ARC-Lake)*. https://datashare.ed.ac.uk/handle/10283/88

ESA. (2025b). *Summary of RESETlakes (REmote SEnsing of Tipping points in Lakes)*. ESA Climate Office. https://climate.esa.int/en/tipping-points-research/about-resetlakes/about-resetlakes/

European Environment Agency. (2018, julio 3). *Quality element status*. https://www.eea.europa.eu/en/analysis/maps-and-charts/quality-elements-of-water-bodies-water-assessments

Falkenmark, M., & Rockström, J. (2004). *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. Earthscan.

Falvey, M., & Garreaud, R. D. (2009). Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). *Journal of Geophysical Research: Atmospheres*, *114*(D4). https://doi.org/10.1029/2008JD010519

Fang, G. H., Yang, J., Chen, Y. N., & Zammit, C. (2015). Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, *19*(6), 2547-2559. https://doi.org/10.5194/hess-19-2547-2015

Fang, X., & An, D. (2022). Evaluation on sea surface wind speed product of Fengyun-3D satellite microwave radiation imager using ERA-5 dataset. *International Journal of Remote Sensing*, *43*(10), 3671-3691. https://doi.org/10.1080/01431161.2022.2099770

Fang, X., & Stefan, H. G. (1996). Dynamics of heat exchange between sediment and water in a lake. *Water Resources Research*, *32*(6), 1719-1727. https://doi.org/10.1029/96WR00274

FAO. (2025). *NEW! Check out the Open Foris interactive story*. OpenForis. https://www.fao.org/in-action/openforis/en

Farnaz Nojavan, F. N., Kreakie, B. J., Hollister, J. W., & Qian, S. S. (2019). Rethinking the lake trophic state index. *PeerJ*, *7*, e7936. https://doi.org/10.7717/peerj.7936

Fatichi, S. (2025, agosto 1). *Mann-Kendall Test (https://www.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test), MATLAB Central File Exchange. Recuperado 1 agosto, 2025.* https://la.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test

Fernández, I. C., Manuel-Navarrete, D., & Torres-Salinas, R. (2016). Breaking resilient patterns of inequality in Santiago de Chile: Challenges to navigate towards a more sustainable city. *Sustainability*, *8*(8), 820. https://www.mdpi.com/2071-1050/8/8/820

Fernández-Manjarrés, J. F., Roturier, S., & Bilhaut, A.-G. (2018). The emergence of the social-ecological restoration concept. *Restoration Ecology*, *26*(3), 404-410. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.12685

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302-4315. https://doi.org/10.1002/joc.5086

Fischer, R., Tamayo Cordero, F., Ojeda Luna, T., Ferrer Velasco, R., DeDecker, M., Torres, B., Giessen, L., & Günter, S. (2021). Interplay of governance elements and their effects on deforestation in tropical landscapes: Quantitative insights from Ecuador. *World Development*, *148*, 105665. https://www.sciencedirect.com/science/article/pii/S0305750X21002801

Fitchett, L. L., Sorice, M. G., Cobourn, K. M., Boyle, K. J., Klug, J. L., & Weathers, K. C. (2020). Pathways to enhanced lake integrity: A Framework to assess the effectiveness of local lake associations. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *25*(2), 258-268. https://doi.org/10.1111/lre.12308

Flavelle, A. (2003). *Mapping Our Land: Community Mapping Handbook*. Lone Pine.

Fluet-Chouinard, E., Stocker, B. D., Zhang, Z., Malhotra, A., Melton, J. R., Poulter, B., Kaplan, J. O., Goldewijk, K. K., Siebert, S., Minayeva, T., Hugelius, G., Joosten, H., Barthelmes, A., Prigent, C., Aires, F., Hoyt, A. M., Davidson, N., Finlayson, C. M., Lehner, B., … McIntyre, P. B. (2023). Extensive global wetland loss over the past three centuries. *Nature*, *614*(7947), 281-286. https://www.nature.com/articles/s41586-022-05572-6

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R., Chapin, F. S., Seto, K. C., Weber, E. U., Crona, B. I., Daily, G. C., Dasgupta, P., Gaffney, O., Gordon, L. J., Hoff, H., Levin, S. A., … Walker, B. H. (2021). Our future in the Anthropocene biosphere. *Ambio*, *50*(4), 834-869. https://doi.org/10.1007/s13280-021-01544-8

Foster, J. B. (2022). *Capitalism in the Anthropocene: Ecological Ruin or Ecological Revolution*. NYU Press.

Foster, J. B., Clark, B., & York, R. (2011). *The Ecological Rift: Capitalism's War on the Earth*. NYU Press.

Frappart, F., Blarel, F., Fayad, I., Bergé-Nguyen, M., Crétaux, J.-F., Shu, S., Schregenberger, J., & Baghdadi, N. (2021). Evaluation of the Performances of Radar and Lidar Altimetry Missions for Water Level Retrievals in Mountainous Environment: The Case of the Swiss Lakes. *Remote Sensing*, *13*(11), 2196. https://doi.org/10.3390/rs13112196

Frassl, M. A., Boehrer, B., Holtermann, P. L., Hu, W., Klingbeil, K., Peng, Z., Zhu, J., & Rinke, K. (2018). Opportunities and Limits of Using Meteorological

Reanalysis Data for Simulating Seasonal to Sub-Daily Water Temperature Dynamics in a Large Shallow Lake. *Water*, *10*(5), Article 5. https://doi.org/10.3390/w10050594

Freshwater Health Index. (2025). Freshwater Health Index. https://www.freshwaterhealthindex.org

Fuentes, I., Fuster, R., Avilés, D., & Vervoort, W. (2021). Water scarcity in central Chile: The effect of climate and land cover changes on hydrologic resources. *Hydrological Sciences Journal*, *66*(6), 1028-1044. https://doi.org/10.1080/02626667.2021.1903475

Fuentes-Hernández, P., Barría-Catalán, T., & Flores-Chávez, J. (2024). Estado, ferrocarril y territorio: Las estrategias gubernamentales para la ocupación de La Araucanía a fines del siglo XIX. *Revista Austral de Ciencias Sociales*, (46), Article 46. http://revistas.uach.cl/index.php/racs/article/view/7557

Fuenzalida, H. (1982). A country of extreme climate. *Chile: Essence and Evolution*, 27-35.

Fundación Terram. (2021). *MINUTA RELATIVA A LA MORTALIDAD MASIVA DE SALMONES CAUSADAS POR FLORACIONES ALGALES NOCIVAS (FAN) EN LAS REGIONES DE LOS LAGOS Y AYSÉN*. https://www.terram.cl/descargar/recursos_naturales/salmonicultura/Minuta-Mortalidad-Masiva-de-Salmones-en-Los-Lagos-y-AyseCC81n.pdf

Fustos-Toribio, I., Manque-Roa, N., Vásquez Antipan, D., Hermosilla Sotomayor, M., & Letelier Gonzalez, V. (2022). Rainfall-induced landslide early warning system based on corrected mesoscale numerical models: An application for the southern Andes. *Natural Hazards and Earth System Sciences*, *22*(6), 2169-2183. https://doi.org/10.5194/nhess-22-2169-2022

Galarce, L. C. (2020, julio 3). Protección de los ecosistemas acuáticos ante la presión de la crisis económica que viene. *CIPER Chile*. https://www.ciperchile.cl/2020/07/03/proteccion-de-los-ecosistemas-acuaticos-ante-la-presion-de-la-crisis-economica-que-viene/

Gao, H., Birkett, C., & Lettenmaier, D. P. (2012). Global monitoring of large reservoir storage from satellite remote sensing. *Water Resources Research*, *48*(9). https://doi.org/10.1029/2012WR012063

Gao, Y., Xie, Y., & Zou, D. (2020). Hydrological regime change and its ecological responses in East Dongting Lake, China. *Ecohydrology & Hydrobiology*, *20*(1), 142-150. https://doi.org/10.1016/j.ecohyd.2019.07.003

Garreaud, R. D. (2009). The Andes climate and weather. *Advances in Geosciences*, *22*, 3-11. https://doi.org/10.5194/adgeo-22-3-2009

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., & Veloso-Aguila, D. (2020). The Central Chile Mega Drought (2010–2018): A climate dynamics perspective. *International Journal of Climatology*, *40*(1), 421-439. https://doi.org/10.1002/joc.6219

Garreaud, R. D., Vuille, M., Compagnucci, R., & Marengo, J. (2009). Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology, Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives*, *281*(3), 180-195. https://doi.org/10.1016/j.palaeo.2007.10.032

Gell, P. A., Finlayson, C. M., & Davidson, N. C. (2023). 1—An introduction to the Ramsar Convention on Wetlands. En P. A. Gell, N. C. Davidson, & C. M.

Finlayson (Eds.), *Ramsar Wetlands* (pp. 1-36). Elsevier. https://doi.org/10.1016/B978-0-12-817803-4.00018-8

Gerding, V. (2010). *Suelos de humedales y trumaos húmedos del sur de Chile*. http://biblioteca.cehum.org/handle/CEHUM2018/1628

Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. *Sensors*, *16*(8), 1298. https://doi.org/10.3390/s16081298

Gozingan, A. S., Sohou, Z., Baetens, K., Bonou, F., Baloïtcha, E., Gourgue, O., Romanelli, H., Capet, A., & Lacroix, G. (2024). A 3D numerical baroclinic application of the COHERENS model in the Gulf of Guinea, West Africa. *Regional Studies in Marine Science*, *79*, 103811. https://doi.org/10.1016/j.rsma.2024.103811

Granata, F., & Di Nunno, F. (2025). Pathways for Hydrological Resilience: Strategies for Adaptation in a Changing Climate. *Earth Systems and Environment*. https://doi.org/10.1007/s41748-024-00567-x

Gubrium, J. F., Holstein, J. A., Marvasti, A. B., & McKinney, K. D. (2012). *The SAGE Handbook of Interview Research: The Complexity of the Craft*. SAGE Publications.

Gudynas, E. (2014). *Cuando los extractivismos reconfiguran democracias y derechos Tensiones y contradicciones bajo el progresismo realmente gobernante*.

Gudynas, E. (2015). *Derechos de la naturaleza: Ética biocéntrica y políticas ambientales*. Editorial Abya-Yala. https://books.google.es/books?hl=es&lr=&id=FONZEAAAQBAJ&oi=fnd&pg=PA5&dq=gudynas+2015+pol%C3%ADticas+ambientales&ots=XWxfwm2CuX&sig=WCdqNCNGMdVkOrztuZc7SztKDPU

Gudynas, E. (2017). Beyond varieties of development: Disputes and alternatives. En *Rising Powers and South-South Cooperation*. Routledge.

Guo, M., Zhuang, Q., Yao, H., Golub, M., Leung, L. R., Pierson, D., & Tan, Z. (2021). Validation and Sensitivity Analysis of a 1-D Lake Model Across Global Lakes. *Journal of Geophysical Research: Atmospheres*, *126*(4), e2020JD033417. https://doi.org/10.1029/2020JD033417

Guo, Y., Ren, Z., Dong, Y., Zhang, P., Wang, C., Ma, Z., & He, X. (2023). Multifunctionality can be promoted by increasing agriculture-dominated heterogeneous landscapes in an agro-forestry interlacing zone in northeast China. *Landscape and Urban Planning*, *238*, 104832. https://doi.org/10.1016/j.landurbplan.2023.104832

Hammer, D. A., & Bastian, R. K. (1989). Wetlands Ecosystems: Natural Water Purifiers? En *Constructed Wetlands for Wastewater Treatment*. CRC Press.

Hansen, G. J. A., Wehrly, K. E., Vitense, K., Walsh, J. R., & Jacobson, P. C. (2022). Quantifying the resilience of coldwater lake habitat to climate and land use change to prioritize watershed conservation. *Ecosphere*, *13*(7), e4172. https://doi.org/10.1002/ecs2.4172

Hansen, G., & Stone, D. (2016). Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, *6*(5), 532-537. https://doi.org/10.1038/nclimate2896

Hargrove, A. (2021). The global water crises: A cross-national analysis of metabolic rift theory. *Journal of Political Ecology*, *28*, 2925. https://doi.org/10.2458/jpe.2925

Haustein, K., Allen, M. R., Forster, P. M., Otto, F. E. L., Mitchell, D. M., Matthews, H. D., & Frame, D. J. (2017). A real-time Global Warming Index. *Scientific Reports*, *7*(1), 15417. https://doi.org/10.1038/s41598-017-14828-5

He, C., Malcolm, S. B., Dahlberg, K. A., & Fu, B. (2000). A conceptual framework for integrating hydrological and biological indicators into watershed management. *Landscape and Urban Planning*, *49*(1), 25-34. https://doi.org/10.1016/S0169-2046(00)00047-5

Heilmayr, R., Echeverría, C., Fuentes, R., & Lambin, E. F. (2016). A plantation-dominated forest transition in Chile. *Applied Geography*, *75*, 71-82. https://www.sciencedirect.com/science/article/pii/S0143622816302600

Hernandez, D., Mendoza, P. A., Boisier, J. P., & Ricchetti, F. (2022). Hydrologic Sensitivities and ENSO Variability Across Hydrological Regimes in Central Chile (28°–41°S). *Water Resources Research*, *58*(9), e2021WR031860. https://doi.org/10.1029/2021WR031860

Herod, A. (1993). Gender Issues in the Use of Interviewing as a Research Method∗. *The Professional Geographer*, *45*(3), 305-317. https://doi.org/10.1111/j.0033-0124.1993.00305.x

Hersbach. (2023). *ERA5 hourly data on single levels from 1940 to present*. https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview

Hipsey, M. R., Bruce, L. C., Boon, C., Busch, B., Carey, C. C., Hamilton, D. P., Hanson, P. C., Read, J. S., de Sousa, E., Weber, M., & Winslow, L. A. (2019). A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geoscientific Model Development*, *12*(1), 473-523. https://doi.org/10.5194/gmd-12-473-2019

Hodges, B. R., Imberger, J., & Laval, B. (2000). *Modeling the Hydrodynamics of Stratified Lakes*.

Holling, C. S. (1986). The resilience of terrestrial ecosystems: Local surprise and global change. *Sustainable development of the biosphere*, *14*, 292-317.

Hosseini-Sadabadi, S. A., Rousseau, A. N., Sadeghian, A., Foulon, E., & Behmel, S. (2023). A 3D numerical modeling of the links between hydrodynamics, dissolved oxygen, and water temperature of a northern rural-urban shallow lake with two distinct basins. *Environmental Monitoring and Assessment*, *195*(10), 1198. https://doi.org/10.1007/s10661-023-11744-2

Hou, M., Wei, J., Chu, H., Shi, Y., Ayantobo, O. O., Xu, J., Zhu, X., & Ren, Y. (2022). Conceptual hydrological model-guided SVR approach for monthly lake level reconstruction in the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *44*, 101271. https://doi.org/10.1016/j.ejrh.2022.101271

Hu, S., Niu, Z., & Chen, Y. (2017). Global Wetland Datasets: A Review. *Wetlands*, *37*(5), 807-817. https://doi.org/10.1007/s13157-017-0927-z

Hu, S., Niu, Z., Chen, Y., Li, L., & Zhang, H. (2017). Global wetlands: Potential distribution, wetland loss, and status. *Science of The Total Environment*, *586*, 319-327. https://www.sciencedirect.com/science/article/pii/S0048969717302425

Huang, J., Yu, H., Han, D., Zhang, G., Wei, Y., Huang, J., An, L., Liu, X., & Ren, Y. (2020). Declines in global ecological security under climate change. *Ecological Indicators*, *117*, 106651. https://www.sciencedirect.com/science/article/pii/S1470160X20305884

Huang, L., Wang, J., & Chen, X. (2022). Ecological infrastructure planning of large river basin to promote nature conservation and ecosystem functions. *Journal of Environmental Management*, *306*, 114482. https://www.sciencedirect.com/science/article/pii/S030147972200055X

Huang, L., Woolway, R. I., Timmermann, A., Lee, S.-S., Rodgers, K. B., & Yamaguchi, R. (2024). Emergence of lake conditions that exceed natural temperature variability. *Nature Geoscience*, *17*(8), 763-769. https://doi.org/10.1038/s41561-024-01491-5

Huenupil-Marihuen., M., Garces-Vargas, M., Llevilao-Colil, O., L., A.-P., & Medina-Riquelme, F. (2010). *Historia de Tirúa*.

Huttula, T., & Liukko, N. (2014). *Lake Pyykösjärvi water quality model*.

IDE. (2025). *Infraestructura de datos espaciales. Geoportal de Chile*. https://www.geoportal.cl/catalog

IDE minagri. (2025). *Planificación Catastral | IDE minagri*. https://ide.minagri.gob.cl/geoweb/2019/11/22/planificacion-catastral/

Imberger, J., & Patterson, J. C. (1989). Physical Limnology. En J. W. Hutchinson & T. Y. Wu (Eds.), *Advances in Applied Mechanics* (Vol. 27, pp. 303-475). Elsevier. https://doi.org/10.1016/S0065-2156(08)70199-6

INEa. (2017). *ArcGIS Web Application*. https://ine-chile.maps.arcgis.com/apps/webappviewer/index.html?id=d0bff7af90384faa98d6ff69faa0d6d2

INEb. (2024). *Censo de Población y Vivienda*. Default. http://www.ine.gob.cl/estadisticas/sociales/censos-de-poblacion-y-vivienda/censo-de-poblacion-y-vivienda

INFOR, I. (2014). *Exportaciones forestales chilenas 2013*. INFOR. https://doi.org/10.52904/20.500.12220/20791

Interferencia. (2023, febrero 14). *Ministro de Economía confirma postergación de debate sobre nueva regulación forestal planteada por Boric*. Interferencia. https://interferencia.cl/articulos/ministro-de-economia-confirma-postergacion-de-debate-sobre-nueva-regulacion-forestal

International Lake Environment Committee, I. L. E. C. (2007). Integrated lake basin management: An introduction. *International Lake Environment Committee Foundation. Kusatsu, Japan*, *26*.

International Lake EnvironmentCommitte, I. L. E. (2005). *Managing lakes and their basins for sustainable use: A report for lake basin managers and stakeholders*. International Lake Environment Committee Foundation. https://cir.nii.ac.jp/crid/1971430859734593319

Ishikawa, M., Gonzalez, W., Golyjeswski, O., Sales, G., Rigotti, J. A., Bleninger, T., Mannich, M., & Lorke, A. (2022). Effects of dimensionality on the performance of hydrodynamic models for stratified lakes and reservoirs. *Geoscientific Model Development*, *15*(5), 2197-2220. https://doi.org/10.5194/gmd-15-2197-2022

Iturra Urzúa, J. M. (2024). *Saqueo al humedal de Quilicura. Construcciones sobre el agua*. https://repositorio.uchile.cl/handle/2250/198083

Jacques Coper, M., & Garreaud Salazar, R. (2015). *Characterization of the 1970s climate shift in South America*. https://doi.org/10.1002/joc.4120

Jansen, J., Simpson, G. L., Weyhenmeyer, G. A., Härkönen, L. H., Paterson, A. M., del Giorgio, P. A., & Prairie, Y. T. (2024). Climate-driven deoxygenation of

northern lakes. *Nature Climate Change*, *14*(8), 832-838. https://doi.org/10.1038/s41558-024-02058-3
Jerlov. (1968). *Optical Oceanography*. Elsevier.
Ji, L., Senay, G. B., & Verdin, J. P. (2015). *Evaluation of the Global Land Data Assimilation System (GLDAS) Air Temperature Data Products*. https://doi.org/10.1175/JHM-D-14-0230.1
Jian, J., Ryu, D., Costelloe, J. F., & Su, C.-H. (2017). Towards hydrological model calibration using river level measurements. *Journal of Hydrology: Regional Studies*, *10*, 95-109. https://doi.org/10.1016/j.ejrh.2016.12.085
Jiang, Q., Li, W., Fan, Z., He, X., Sun, W., Chen, S., Wen, J., Gao, J., & Wang, J. (2021). Evaluation of the ERA5 reanalysis precipitation dataset over Chinese Mainland. *Journal of Hydrology*, *595*, 125660. https://doi.org/10.1016/j.jhydrol.2020.125660
Jorgensen, S. E., & Rast, W. (2007). The use of models for synthesizing knowledge for integrated lake basin management, and facilitating implementation of the World Lake Vision. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *12*(1), 3-13. https://doi.org/10.1111/j.1440-1770.2007.00316.x
Kanazawa, M. (2023). *Research Methods for Environmental Studies: A Social Science Approach* (2.ª ed.). Routledge. https://doi.org/10.4324/9781003261117
Kay, J. J., & Schneider, E. (1995). Embracing Complexity the Challenge of the Ecosystem Approach. En L. Westra & J. Lemons (Eds.), *Perspectives on Ecological Integrity* (pp. 49-59). Springer Netherlands. https://doi.org/10.1007/978-94-011-0451-7_4
Kaya, Y. (2025). Evaluation of ICESat-2 Laser Altimetry for Inland Water Level Monitoring: A Case Study of Canadian Lakes. *Water*, *17*(7), 1098. https://doi.org/10.3390/w17071098
Kaya, Y., Balik Sanli, F., & Abdikan, S. (2025). Refinement of ICESat-2 derived inland water surface levels with the TG20 local geoid model: In the case of Türkiye lakes. *Physics and Chemistry of the Earth, Parts A/B/C*, *139*, 103900. https://doi.org/10.1016/j.pce.2025.103900
King, A. W. (1993). Considerations of Scale and Hierarchy. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.
Kirby, R. R., Beaugrand, G., Kleparski, L., Goodall, S., & Lavender, S. (2021). Citizens and scientists collect comparable oceanographic data: Measurements of ocean transparency from the Secchi Disk study and science programmes. *Scientific Reports*, *11*(1), 15499. https://doi.org/10.1038/s41598-021-95029-z
KNMI. (2024). *KNMI Climate explorer*. https://climexp.knmi.nl/selectindex.cgi?id=someone@somewhere
Kondo, J. (1975). Air-sea bulk transfer coefficients in diabatic conditions. *Boundary-Layer Meteorology*, *9*(1), 91-112. https://doi.org/10.1007/BF00232256
Korkou, M., Tarigan, A. K. M., & Hanslin, H. M. (2023). The multifunctionality concept in urban green infrastructure planning: A systematic literature review. *Urban Forestry & Urban Greening*, *85*, 127975. https://doi.org/10.1016/j.ufug.2023.127975
Kornijów, R. (2023). Lake aging concept revisited: Alternative comprehensive approach to lake ontogeny. *Canadian Journal of Fisheries and Aquatic Sciences*, *80*(8), 1385-1393. https://doi.org/10.1139/cjfas-2023-0027

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259-263. https://doi.org/10.1127/0941-2948/2006/0130

Kreakie, B. J., Shivers, S. D., Hollister, J. W., & Milstead, W. B. (2021). Predictive Model of Lake Photic Zone Temperature Across the Conterminous United States. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.707874

Kumar, L., & Mutanga, O. (2018). Google Earth Engine Applications Since Inception: Usage, Trends, and Potential. *Remote Sensing*, *10*(10), Article 10. https://doi.org/10.3390/rs10101509

Kwak, T. J., & Freeman, M. (2010). *Assessment and management of ecological integrity: Chapter 12*. 353-394. https://pubs.usgs.gov/publication/70154946

Labraña-Muñoz, C., & Arcas-Morales, G. (2006). San Pedro de la Paz: Del Fuerte a la comuna (1604-2001). *Hualpén, Chile: Impresos Andalién, Ilustre Municipalidad de San Pedro de la Paz*.

Lara, A., Jones, J., Little, C., & Vergara, N. (2021). Streamflow response to native forest restoration in former Eucalyptus plantations in south central Chile. *Hydrological Processes*, *35*(8), e14270. https://doi.org/10.1002/hyp.14270

Lara, A., Solari, M. E., Prieto, M. D. R., & Peña, M. P. (2012). Reconstrucción de la cobertura de la vegetación y uso del suelo hacia 1550 y sus cambios a 2007 en la ecorregión de los bosques valdivianos lluviosos de Chile (35º—43º 30´ S). *Bosque (Valdivia)*, *33*(1), 13-23. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-92002012000100002&lng=es&nrm=iso&tlng=en

Lee, J.-W., Park, S.-R., & Lee, S.-W. (2023). Effect of Land Use on Stream Water Quality and Biological Conditions in Multi-Scale Watersheds. *Water*, *15*(24), 4210. https://doi.org/10.3390/w15244210

Lee, K., Nam, S., Cho, Y.-K., Jeong, K.-Y., & Byun, D.-S. (2022). Determination of Long-Term (1993–2019) Sea Level Rise Trends Around the Korean Peninsula Using Ocean Tide-Corrected, Multi-Mission Satellite Altimetry Data. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.810549

Lewis, S. L., & Maslin, M. A. (2015). Defining the Anthropocene. *Nature*, *519*(7542), 171-180. https://www.nature.com/articles/nature14258

Lieberherr, G., & Wunderle, S. (2018). Lake Surface Water Temperature Derived from 35 Years of AVHRR Sensor Data for European Lakes. *Remote Sensing*, *10*(7), Article 7. https://doi.org/10.3390/rs10070990

Lin, S., Boegman, L., Shan, S., & Mulligan, R. (2022). An automatic lake-model application using near-real-time data forcing: Development of an operational forecast workflow (COASTLINES) for Lake Erie. *Geoscientific Model Development*, *15*(3), 1331-1353. https://doi.org/10.5194/gmd-15-1331-2022

Little, C., Lara, A., McPhee, J., & Urrutia, R. (2009). Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile. *Journal of Hydrology*, *374*(1), 162-170. https://doi.org/10.1016/j.jhydrol.2009.06.011

Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., Valenzuela, R. A., Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., & Valenzuela, R. A. (2017). La agricultura y la élite agraria chilena a través de los catastros agrícolas, c. 1830-1855. *Historia (Santiago)*, *50*(2), 597-639.

http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-71942017000200597&lng=es&nrm=iso&tlng=es

Long, L. (2017, marzo 1). The Stages of Lake and Pond Succession. *SOLitude Lake Management: Full-Service Lake And Pond Management*. https://www.solitudelakemanagement.com/the-stages-of-lake-and-pond-succession/

Lovell, S. T. (2010). Multifunctional Urban Agriculture for Sustainable Land Use Planning in the United States. *Sustainability*, *2*(8), 2499-2522. https://doi.org/10.3390/su2082499

Luo, J., Duan, H., Xu, Y., Shen, M., Zhang, Y., Xiao, Q., Ni, G., Wang, K., Xin, Y., Qi, T., Feng, L., Qiu, Y., Jeppesen, E., & Woolway, R. I. (2025). Global trends and regime state shifts of lacustrine aquatic vegetation. *The Innovation*, *6*(3), 100784. https://doi.org/10.1016/j.xinn.2024.100784

Luyten, P. (2025). *COHERENS: A Coupled Hydrodynamical Ecological Model for Regional and Shelf Seas: User Documentation (Version 3)*. Operational Directorate Natural Environment, Royal Belgian Institute of Natural Sciences. https://doi.org/10.5281/zenodo.11261106.

Lyche Solheim, A., Globevnik, L., Austnes, K., Kristensen, P., Moe, S. J., Persson, J., Phillips, G., Poikane, S., van de Bund, W., & Birk, S. (2019). A new broad typology for rivers and lakes in Europe: Development and application for large-scale environmental assessments. *Science of The Total Environment*, *697*, 134043. https://doi.org/10.1016/j.scitotenv.2019.134043

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J. B., Jena, J., Bhattacharya, U., Duvvada, S. K., Lalichetti, S., & Sairam, M. (2021). Intercropping—A Low Input Agricultural Strategy for Food and Environmental Security. *Agronomy*, *11*(2), Article 2. https://www.mdpi.com/2073-4395/11/2/343

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015a). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*, 331-340. https://doi.org/10.1016/j.agwat.2015.06.022

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015b). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*(C), 331-340. https://ideas.repec.org//a/eee/agiwat/v159y2015icp331-340.html

Mano, A., Malve, O., Koponen, S., Kallio, K., Taskinen, A., Ropponen, J., Juntunen, J., & Liukko, N. (2015). Assimilation of satellite data to 3D hydrodynamic model of Lake Säkylän Pyhäjärvi. *Water Science and Technology*, *71*(7), 1033-1039. https://doi.org/10.2166/wst.2015.042

Mano, A., & Shuku, T. (2014). *Application of the Particle Filter to COHERENS V2 model of Lake Säkylän Pyhäjärvi*.

Manuschevich, D. (2016). Neoliberalization of forestry discourses in Chile. *Forest Policy and Economics*, *69*, 21-30. https://doi.org/10.1016/j.forpol.2016.03.006

Marinov, D., Norro, A., & Zaldívar, J.-M. (2006). Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore). *Ecological Modelling, Special Issue on Southern European Coastal Lagoons*, *193*(1), 52-68. https://doi.org/10.1016/j.ecolmodel.2005.07.042

Martínez Retureta, R. (2021). *Efectos del cambio de uso cobertura del suelo sobre la respuesta hidrológica en cuencas del centro sur de Chile bajo escenarios de cambio climático.* https://repositorio.udec.cl/handle/11594/6538

Martínez-Fernández, J., Banos-González, I., & Esteve-Selma, M. Á. (2021). An integral approach to address socio-ecological systems sustainability and their uncertainties. *Science of The Total Environment*, *762*, 144457. https://www.sciencedirect.com/science/article/pii/S0048969720379882

Martínez-Tilleria, K., Núñez-Ávila, M., León, C. A., Pliscoff, P., Squeo, F. A., & Armesto, J. J. (2017). A framework for the classification Chilean terrestrial ecosystems as a tool for achieving global conservation targets. *Biodiversity and Conservation*, *26*(12), 2857-2876. https://doi.org/10.1007/s10531-017-1393-x

Marttunen, M., Hellsten, S., Glover, B., Tarvainen, A., Klintwall, L., Olsson, H., & Pedersen, T. S. (2006). Heavily regulated lakes and the European Water framework directive—Comparisons from Finland, Norway, Sweden, Scotland and Austria. *E-Water*, *5*, 1-22. https://www.ewa-online.eu/files/downloads/publications/E-Water_Journal/42_2006_05.pdf

Mason, I. M., Guzkowska, M. A. J., Rapley, C. G., & Street-Perrott, F. A. (1994). The response of lake levels and areas to climatic change. *Climatic Change*, *27*(2), 161-197. https://doi.org/10.1007/BF01093590

Mayer, A. L., & Rietkerk, M. (2004). The Dynamic Regime Concept for Ecosystem Management and Restoration. *BioScience*, *54*(11), 1013-1020. https://doi.org/10.1641/0006-3568(2004)054[1013:TDRCFE]2.0.CO;2

McDougall, T. J., Jackett, D. R., Wright, D. G., & Feistel, R. (2003). *Accurate and Computationally Efficient Algorithms for Potential Temperature and Density of Seawater*. https://journals.ametsoc.org/view/journals/atot/20/5/1520-0426_2003_20_730_aaceaf_2_0_co_2.xml

McGregor, G. (2017). Hydroclimatology, modes of climatic variability and stream flow, lake and groundwater level variability: A progress report. *Progress in Physical Geography: Earth and Environment*, *41*(4), 496-512. https://doi.org/10.1177/0309133317726537

Meerhoff, M., Audet, J., Davidson, T. A., De Meester, L., Hilt, S., Kosten, S., Liu, Z., Mazzeo, N., Paerl, H., Scheffer, M., & Jeppesen, E. (2022). Feedback between climate change and eutrophication: Revisiting the allied attack concept and how to strike back. *Inland Waters*, *12*(2), 187-204. https://doi.org/10.1080/20442041.2022.2029317

Mellor, G. L. (1988). *A THREE-DIMENSIONAL, PRIMITIVE EQUATION, NUMERICAL OCEAN MODEL*.

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016a). Trophic State Index estimation from remote sensing of lake Chapala, México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016b). Trophic State Index estimation from remote sensing of lake Chapala,

México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Meng, B., Liu, J., Bao, K., & Sun, B. (2020). Methodologies and Management Framework for Restoration of Wetland Hydrologic Connectivity: A Synthesis. *Integrated Environmental Assessment and Management*, *16*(4), 438-451. https://doi.org/10.1002/ieam.4256

Merryfield, W. J., & Lee, W.-S. (2023). Estimating Probabilities of Extreme ENSO Events from Copernicus Seasonal Hindcasts. *Asia-Pacific Journal of Atmospheric Sciences*, *59*(4), 479-493. https://doi.org/10.1007/s13143-023-00328-2

Metcalfe, A. N., Kennedy, T. A., Mendez, G. A., & Muehlbauer, J. D. (2022). Applied citizen science in freshwater research. *WIREs Water*, *9*(2), e1578. https://doi.org/10.1002/wat2.1578

Mironov, D., Golosov, S., Heise, E., Kourzeneva, E., Ritter, B., Schneider, N., & Terzhevik, A. (2005). FLake – A Lake Model for Environmental Applications. *2005*.

Mitra, S., Wassmann, R., & Vlek, P. L. G. (2003). *Global inventory of wetlands and their role in the carbon cycle* (ZEF - Discussion Papers on Development Policy No. 64). https://doi.org/10.22004/ag.econ.18771

MMA. (2020). *ANTEPROYECTO DEL PLAN DE DESCONTAMINACION POR CLOROFILA "A", TliANSPARENCIA Y FOSFORO DISUELTO, PARA LA CUENCA DEL LAGO VILLARRICA.* https://consultaindigena.mma.gob.cl/wp-content/uploads/2021/11/Anteproyecto-PDA-Lago-Villarrica.pdf

Montecinos, A., & Aceituno, P. (2003). *Seasonality of the ENSO-Related Rainfall Variability in Central Chile and Associated Circulation Anomalies*. https://journals.ametsoc.org/view/journals/clim/16/2/1520-0442_2003_016_0281_soterr_2.0.co_2.xml

Morales-Magaña, M., Paneque-Galvez, J., Torres-Abreu, A., Mori-González, R., Reyes Díaz, A. M., Rivera Ramos, J. C., Molina Carrasquillo, R., & Molina Parrilla, S. C. (2020). *Community experiences in water management: Social innovation, participatory science, and dialogue of knowledges II (in Portuguese and Spanish)*. https://doi.org/10.5281/zenodo.4362629

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, *50*(3), 885-900. https://doi.org/10.13031/2013.23153

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). *Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria*.

Mortimer, C. H. (1974). Lake hydrodynamics. *Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Mitteilungen*. (world). https://www.tandfonline.com/doi/abs/10.1080/05384680.1974.11923886

Mukaka, M. M. (2012). A guide to appropriate use of Correlation coefficient in medical research. *Malawi Medical Journal*, *24*(3), 69-71. https://www.ajol.info/index.php/mmj/article/view/81576

Muñoz Aguayo, P. (2013). *Apuntes de teledetección: Índices de vegetación.* https://bibliotecadigital.ciren.cl/bitstreams/af8fd625-0d58-4941-8530-7186a6b3d93e/download

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349-4383. https://doi.org/10.5194/essd-13-4349-2021

Naciones Unidas, M. J. (2025). Objetivos y metas de desarrollo sostenible. *Desarrollo Sostenible*. https://www.un.org/sustainabledevelopment/es/objetivos-de-desarrollo-sostenible/

NASA. (2025). *ASF Data Search*. https://search.asf.alaska.edu/

NASA SWOT. (2024). *NASA SWOT. Jet Propulsion Laboratory: Surface Water and Ocean Topography (SWOT).* https://swot.jpl.nasa.gov/

National Institute of Water and Atmospheric Research. (2025). *Lakespi (Lake Submerged Plant Indicators)*. https://lakespi.niwa.co.nz/

Ndehedehe, C. E., Awange, J. L., Kuhn, M., Agutu, N. O., & Fukuda, Y. (2017). Analysis of hydrological variability over the Volta river basin using in-situ data and satellite observations. *Journal of Hydrology: Regional Studies*, *12*, 88-110. https://doi.org/10.1016/j.ejrh.2017.04.005

Nekouee, N., Hamidi, S. A., Roberts, P. J. W., & Schwab, D. J. (2015). Assessment of a 3D Hydrostatic Model (POM) in the Near Field of a Buoyant River Plume in Lake Michigan. *Water, Air, & Soil Pollution*, *226*(7), 210. https://doi.org/10.1007/s11270-015-2488-1

Ngamile, S., Madonsela, S., & Kganyago, M. (2025). Trends in remote sensing of water quality parameters in inland water bodies: A systematic review. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1549301

Nhamo, L., Magidi, J., & Dickens, C. (2017). Determining wetland spatial extent and seasonal variations of the inundated area using multispectral remote sensing. *Water SA*, *43*(4), 543-552. https://doi.org/10.4314/wsa.v43i4.02

Nielsen, L. (2020, enero). *(PDF) Toward a unified theory of risk, resilience and sustainability science with applications for education and governance*. https://www.researchgate.net/publication/348407042_Toward_a_unified_theory_of_risk_resilience_and_sustainability_science_with_applications_for_education_and_governance

NOAA. (2024a). *El Niño / Southern Oscillation (ENSO) | Equatorial Pacific Sea Surface Temperatures (SST) | National Centers for Environmental Information (NCEI)*. https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024b). *National Oceanic and Atmospheric Administration (NOAA). Antartic Oscillation.* https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml

NOAA. (2024c). *National Oceanic and Atmospheric Administration (NOAA). Equatorial Pacific Sea Surface Temperatures (SST).* https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024d). *National Oceanic and Atmospheric Administration (NOAA). Pacific Decadal Oscillation (PDO).* https://www.ncei.noaa.gov/access/monitoring/pdo/

Odeku, K. O. (2022). Climate injustices due to the unequal and disproportionate impacts of climate change. *Perspectives of Law and Public Administration*, *11*(1), 103-110. https://www.ceeol.com/search/article-detail?id=1102605

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., & Calvez, R. (2018). Surface water monitoring in small water bodies: Potential and limits of multi-sensor Landsat time series. *Hydrology and Earth System Sciences*, *22*(8), 4349-4380. https://doi.org/10.5194/hess-22-4349-2018

Olvera, M. J. T. (2018). *Integridad ecológica como una herramienta de evaluación en cuencas hidrográficas. Caso de estudio Microcuenca del Río Jalpan*. https://ri-ng.uaq.mx/handle/123456789/1004

Onyutha, C. (2021). A hydrological model skill score and revised R-squared. *Hydrology Research*, *53*(1), 51-64. https://doi.org/10.2166/nh.2021.071

Oppliger, A. (2015). *Atlas del Agua – Chile 2016 / Atlas of Water—Chile 2016*. Ministry of Public Works - General Direction of Waters of Chile. https://iris.unil.ch/handle/iris/49995

O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J. D., McIntyre, P. B., Kraemer, B. M., Weyhenmeyer, G. A., Straile, D., Dong, B., Adrian, R., Allan, M. G., Anneville, O., Arvola, L., Austin, J., Bailey, J. L., … Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, *42*(24), 10,773-10,781. https://doi.org/10.1002/2015GL066235

Organización del Tratado de Cooperación Amazónica. (2025). *Proyecto Cuenca Amazónica. Implementación del Programa de Acciones Estratégicas en la Cuenca del río Amazonas considerando la Variabilidad y el Cambio Climático.* https://aguasamazonicas.otca.org/monitoreo-ambiental-y-de-los-recursos-hidricos/sistema-integrado-de-monitoreo-de-los-recursos-hidricos/

Ortiz, A. M. D., Gayó, E. M., Henríquez, N. C., Henríquez, B. J., & Pauchard, A. (2024). Exploring the multifunctional landscapes model in areas dominated by non-native tree plantations. *Trees, Forests and People*, *17*, 100617. https://www.sciencedirect.com/science/article/pii/S2666719324001249

Otavo, S., & Echeverría, C. (2017). Fragmentación progresiva y pérdida de hábitat de bosques naturales en uno de los hotspot mundiales de biodiversidad. *Revista Mexicana de Biodiversidad*, *88*(4), 924-935. https://doi.org/10.1016/j.rmb.2017.10.041

Otero Durán, L. (2012). La huella del fuego: Historia de los bosques nativos poblamiento y cambios en el paisaje de lsur de Chile. *2012*. https://www.sidalc.net/search/Record/KOHA-OAI-FCF:15776/Description

Oxley, R. L. (2015). *Ecological, environmental and hydrological integrity in sustainable water resource management for river basins*. Arizona State University. https://search.proquest.com/openview/4d57cce5b508c9900cd2f564fdc817bd/1?pq-origsite=gscholar&cbl=18750

Palomo, I., Locatelli, B., Otero, I., Colloff, M., Crouzat, E., Cuni-Sanchez, A., Gómez-Baggethun, E., González-García, A., Grêt-Regamey, A., Jiménez-Aceituno, A., Martín-López, B., Pascual, U., Zafra-Calvo, N., Bruley, E., Fischborn, M., Metz, R., & Lavorel, S. (2021). Assessing nature-based solutions for transformative change. *One Earth*, *4*(5), 730-741. https://doi.org/10.1016/j.oneear.2021.04.013

Paredes, M. L., & Ulloa, M. E. (2021). Implementación de los ECMPO y las disputas por el control del territorio: El caso del ECMPO Mañihueico-Huinay y los mitilicultores de la comuna de Hualaihué, Región de Los Lagos. *Revista LIDER*, 62-87. https://revistas.ulagos.cl/index.php/index

Pareeth, S., Salmaso, N., Adrian, R., & Neteler, M. (2016). Homogenised daily lake surface water temperature data generated from multiple satellite sensors: A long-term case study of a large sub-Alpine lake. *Scientific Reports*, *6*(1), 31251. https://doi.org/10.1038/srep31251

Parra et al. (2016). *Una aproximación interdisciplinaria al estudio... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Una+aproximaci%C3%B3n+interdisciplinaria+al+estudio+de+floraciones+de+algas+nocivas+en+Lagos+Urbanos+En+Chile&author=Parra,+O.&author=Baeza,+C.&author=Almanza,+V.&author=Urrutia,+R.&author=Figueroa,+R.&author=Fern%C3%A1ndez,+X.&author=de+Or%C3%BAe,+P.&author=Gonz%C3%A1lez,+P.&author=Beltr%C3%A1n,+J.&author=Becerra,+J.&publication_year=2016&pages=133%E2%80%93146

Parra et al., O. (2003). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*, 51-83. https://ui.adsabs.harvard.edu/abs/2003Limne..22...51P

Parra, O. (2003a). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://doi.org/10.23818/limn.22.04

Parra, O. (2003b). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://www.limnetica.net/documentos/limnetica/limnetica-22-1-p-51.pdf

Parra, O., Basualto, S., Urrutia, R., & Valdovinos, C. (1999). Estudio comparativo de la diversidad fitoplanctónica de cinco lagos de diferentes niveles de eutroficación del área litoral de la región del Biobio (Chile). *Gayana Botánica (Chile)*, *56*, 93-108.

Parra, O. O. (1989). *La eutroficación de la Laguna Grande de San Pedro, Concepción, Chile: Un caso de estudio.*

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005a). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005b). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Pedreros-Guarda, M. (2025). *Github COHERENS Lake*. https://github.com/mpedreros/COHERENS_Lake.git

Pedreros-Guarda, M. (2025). *Mpedreros/TesisDoctoral* [Software]. https://github.com/mpedreros/TesisDoctoral (Obra original publicada en 2025)

Pedreros-Guarda, M., Abarca-del-Río, R., Crétaux, J. F., & Paris, A. (2025). Long-term lake water levels in central Chile using satellite altimetry and conceptual hydrological modelling approaches. *Advances in Space Research*, *76*(4), 1997-2018. https://doi.org/10.1016/j.asr.2025.05.091

Pedreros-Guarda, M., Abarca-del-Río, R., Escalona, K., García, I., & Parra, Ó. (2021). A Google Earth Engine Application to Retrieve Long-Term Surface Temperature for Small Lakes. Case: San Pedro Lagoons, Chile. *Remote Sensing*, *13*(22), 4544. https://doi.org/10.3390/rs13224544

Piccioni, F., Casenave, C., Lemaire, B. J., Le Moigne, P., Dubois, P., & Vinçon-Leite, B. (2021). The thermal response of small and shallow lakes to climate change:

New insights from 3D hindcast modelling. *Earth System Dynamics*, *12*(2), 439-456. https://doi.org/10.5194/esd-12-439-2021

Piccolroaz, S., Toffolon, M., & Majone, B. (2013). A simple lumped model to convert air temperature into surface water temperature in lakes. *Hydrology and Earth System Sciences*, *17*(8), 3323-3338. https://doi.org/10.5194/hess-17-3323-2013

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024a). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024b). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Pilla, R. M., Williamson, C. E., Zhang, J., Smyth, R. L., Lenters, J. D., Brentrup, J. A., Knoll, L. B., & Fisher, T. J. (2018). Browning-Related Decreases in Water Transparency Lead to Long-Term Increases in Surface Water Temperature and Thermal Stratification in Two Small Lakes. *Journal of Geophysical Research: Biogeosciences*, *123*(5), 1651-1665. https://doi.org/10.1029/2017JG004321

Pinto, A. P., García, P. B., Almonacid, L. E., & Henríquez, B. J. (2023). Zonas de Sacrificio y Recuperación Socioambiental en Chile: Fallas y oportunidades de la política ambiental. *Ambiente & Sociedade*, *26*, e01371. https://www.scielo.br/j/asoc/a/JdDjvNrLpBJPKwYfppfDBWB/

Prats, J., Reynaud, N., Rebière, D., Peroux, T., Tormos, T., & Danis, P.-A. (2018). LakeSST: Lake Skin Surface Temperature in French inland water bodies for 1999–2016 from Landsat archives. *Earth System Science Data*, *10*(2), 727-743. https://doi.org/10.5194/essd-10-727-2018

Qiao, B., Du, T., Ju, J., & Zhu, L. (2025). Water depth inversion based on ICESat-2 and Sentinel-2—A case study of Qiagui Co and Ayakekumu Lake on the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *59*, 102354. https://doi.org/10.1016/j.ejrh.2025.102354

Quevedo, F., Rojas Hernández, J., & Barra, R. O. (2022). Towards a Chilean Water Governance: A Study on the Los Batros and Paicaví Wetland Reservoirs. *Water*, *14*(18), Article 18. https://www.mdpi.com/2073-4441/14/18/2861

Quintana, J. M., & Aceituno, P. (2012). Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30-43º S. *Atmósfera*, *25*(1), 1-22. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S0187-62362012000100001&lng=es&nrm=iso&tlng=en

Randrianiaina, Rakotonirina, Ratiarimanana, & Lahatra. (2018). *Temperature Retrieval of Lake Itasy Using Remote Sensing*. https://scholar.google.com/scholar_lookup?title=Temperature+Retrieval+of+Lake+Itasy+Using+Remote+Sensing&author=Randrianiaina,+J.&author=Rakotonirina,+I.&author=Ratiarimanana,+R.&author=Lahatra,+F.&publication_year=2018&journal=Resour.+Environ.&volume=8&pages=241%E2%80%93244

Regier, H. A. (1993a). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Regier, H. A. (1993b). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Renting, H., Rossing, W. A. H., Groot, J. C. J., Van der Ploeg, J. D., Laurent, C., Perraud, D., Stobbelaar, D. J., & Van Ittersum, M. K. (2009). Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. *Journal of Environmental Management, Multifunctional agriculture - From farm diagnosis to farm design and institutional innovation*, *90*, S112-S123. https://doi.org/10.1016/j.jenvman.2008.11.014

Restrepo, L. A. V., & Sal, A. G. (2008). Un marco conceptual y analítico para estimar la integridad ecológica a escala de paisaje. *Arbor*, *184*(729), Article 729. https://arbor.revistas.csic.es/index.php/arbor/article/view/159

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Roche, P. K., & Campagne, C. S. (2017). From ecosystem integrity to ecosystem condition: A continuity of concepts supporting different aspects of ecosystem sustainability. *Current Opinion in Environmental Sustainability*, *29*, 63-68. https://www.sciencedirect.com/science/article/pii/S1877343517302828

Rockström, J., Donges, J. F., Fetzer, I., Martin, M. A., Wang-Erlandsson, L., & Richardson, K. (2024). Planetary Boundaries guide humanity's future on Earth. *Nature Reviews Earth & Environment*, *5*(11), 773-788. https://www.nature.com/articles/s43017-024-00597-z

Rojas Quezada, C. A., Muñiz Olivera, I., & García-López, M. Á. (2009). Estructura urbana y policentrismo en el Área Metropolitana de Concepción. *EURE (Santiago)*, *35*(105), 47-70. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0250-71612009000200003&lng=es&nrm=iso&tlng=es

Rutllant, J., & Fuenzalida, H. (1991). Synoptic aspects of the central chile rainfall variability associated with the southern oscillation. *International Journal of Climatology*, *11*(1), 63-76. https://doi.org/10.1002/joc.3370110105

Salazar, Á., Thatcher, M., Goubanova, K., Bernal, P., Gutiérrez, J., & Squeo, F. (2024). CMIP6 precipitation and temperature projections for Chile. *Climate Dynamics*, *62*(3), 2475-2498. https://doi.org/10.1007/s00382-023-07034-9

Saloranta, T. M., & Andersen, T. (2007). MyLake—A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations. *Ecological Modelling, Uncertainty in Ecological Models*, *207*(1), 45-60. https://doi.org/10.1016/j.ecolmodel.2007.03.018

San Llorente Capdevila, A., Kokimova, A., Sinha Ray, S., Avellán, T., Kim, J., & Kirschke, S. (2020). Success factors for citizen science projects in water quality monitoring. *Science of The Total Environment*, *728*, 137843. https://doi.org/10.1016/j.scitotenv.2020.137843

Saraceni, M., Brunone, B., Silvestri, L., Meniconi, S., & Cerlini, P. B. (2025). *A Water Mass Balance–Based Procedure Using ERA5 Land Reanalysis and Level*

Observation to Reconstruct the Past Level Changes of Closed Lakes toward Future Management. https://doi.org/10.1175/JHM-D-24-0019.1

Sarkar, D., Kar, S. K., Chattopadhyay, A., Shikha, Rakshit, A., Tripathi, V. K., Dubey, P. K., & Abhilash, P. C. (2020). Low input sustainable agriculture: A viable climate-smart option for boosting food production in a warming world. *Ecological Indicators*, *115*, 106412. https://www.sciencedirect.com/science/article/pii/S1470160X20303496

Sarkar, S., & Maity, R. (2021). Global climate shift in 1970s causes a significant worldwide increase in precipitation extremes. *Scientific Reports*, *11*(1), 11574. https://doi.org/10.1038/s41598-021-90854-8

Sarricolea, P., Herrera-Ossandon, M., & Meseguer-Ruiz, Ó. (2017). Climatic regionalisation of continental Chile. *Journal of Maps*, *13*(2), 66-73. https://doi.org/10.1080/17445647.2016.1259592

Sazib, N., Mladenova, I., & Bolten, J. (2018). Leveraging the Google Earth Engine for Drought Assessment Using Global Soil Moisture Data. *Remote Sensing*, *10*(8), Article 8. https://doi.org/10.3390/rs10081265

Schallenberg, M., de Winton, M. D., & Kelly, D. J. (2018). Indicators of Ecological Integrity. En D. P. Hamilton, K. J. Collier, J. M. Quinn, & C. Howard-Williams (Eds.), *Lake Restoration Handbook: A New Zealand Perspective* (pp. 367-393). Springer International Publishing. https://doi.org/10.1007/978-3-319-93043-5_11

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591-596. https://doi.org/10.1038/35098000

Schmid, M., & Read, J. (2022). Heat budget of lakes. En *Encyclopedia of inland waters* (Vol. 1, pp. 467-473). https://doi.org/10.1016/b978-0-12-819166-8.00011-6

Schmithuesen, F. (2007). Multifunctional forestry practices as a land use strategy to meet increasing private and public demands in modern societies. *Journal of Forest Science - UZPI (Czech Republic)*, *53*(6). https://agris.fao.org/search/en/providers/122644/records/647247a2e17b74d2224f615d

Schott, F. A., Wang, W., & Stammer, D. (2007). Variability of Pacific subtropical cells in the 50-year ECCO assimilation. *Geophysical Research Letters*, *34*(5). https://doi.org/10.1029/2006GL028478

Schwatke, C., Dettmering, D., Bosch, W., & Seitz, F. (2015). DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrology and Earth System Sciences*, *19*(10), 4345-4364. https://doi.org/10.5194/hess-19-4345-2015

Seidl, R., & Barthel, R. (2017). Linking scientific disciplines: Hydrology and social sciences. *Journal of Hydrology*, *550*, 441-452. https://doi.org/10.1016/j.jhydrol.2017.05.008

Shao, G. P., & Bishop, I. J. (2025). Citizen science in river monitoring: A systematic literature review of the whys and hows. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1609084

Shchepetkin, A. F., & McWilliams, J. C. (2003). A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. *Journal of Geophysical Research: Oceans*, *108*(C3). https://doi.org/10.1029/2001JC001047

Shine, K. P. (1984). Parametrization of the shortwave flux over high albedo surfaces as a function of cloud thickness and surface albedo. *Quarterly Journal of the Royal Meteorological Society*, *110*(465), 747-764. https://doi.org/10.1002/qj.49711046511

Simon, D. F., Munoz, G., Dinh, Q. T., Duy, S. V., Kavanagh, K., Smith, R., Husk, B., & Sauvé, S. (2023). Adopt a Lake: Successfully Tracking Harmful Cyanobacterial Blooms in Canadian Surface Waters Through Citizen Science. *Citizen Science: Theory and Practice*, *8*(1). https://doi.org/10.5334/cstp.655

Smagorinsky, J. (1963). *GENERAL CIRCULATION EXPERIMENTS WITH THE PRIMITIVE EQUATIONS*. https://journals.ametsoc.org/view/journals/mwre/91/3/1520-0493_1963_091_0099_gcewtp_2_3_co_2.xml

Smith, L. T. (2016). *A descolonizar las metodologías. Investigación y pueblos indígenas: A descolonizar las metodologías. Investigación y pueblos indígenas*. LOM Ediciones.

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, *10*(2), 126-139. https://doi.org/10.1065/espr2002.12.142

Sobarzo, M. B., Figueroa, D., & Arcos, D. R. (1997). The Influence of Winds and Tides in the Formation of Circulation Layers in a Bay, a Case Study: Concepción Bay, Chile. *Estuarine, Coastal and Shelf Science*, *45*(6), 729-736. https://doi.org/10.1006/ecss.1997.0233

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. *Anthropocene Review*, *2*(1), 81-98. http://www.scopus.com/inward/record.url?scp=84996501052&partnerID=8YFLogxK

Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., & Mironov, D. (2010). First steps of a lake model intercomparison project: LakeMIP. *Boreal environment research*, *15*(2), 191. https://search.proquest.com/openview/d60a3674e3599840e062b6afc6aff527/1?pq-origsite=gscholar&cbl=5500736

Suazo, B. (2014). Fragmentación socioespacial en el barrio Boca Sur, San Pedro de la Paz: La necesidad de implementar una planificación participativa. *Universidad de Concepción*.

Sullivan, C. J., Read, J. S., & Hansen, G. J. A. (2025). Climate-driven alterations of lake thermal regimes. *Limnology and Oceanography*, *70*(8), 2348-2364. https://doi.org/10.1002/lno.70128

Sultana, F. (2022). Critical climate justice. *The Geographical Journal*, *188*(1), 118-124. https://onlinelibrary.wiley.com/doi/abs/10.1111/geoj.12417

Szesztay, K. (1974). Water balance and water level fluctuations of lakes. *Hydrological Sciences Bulletin*, *19*(1), 73-84. http://www.tandfonline.com/doi/abs/10.1080/02626667409493872

Tachikawa, T., Hato, M., Kaku, M., & Iwasaki, A. (2011). Characteristics of ASTER GDEM version 2. *2011 IEEE International Geoscience and Remote Sensing Symposium*, 3657-3660. https://doi.org/10.1109/IGARSS.2011.6050017

Taghizadeh, E., Ahmadi-Givi, F., Brocca, L., & Sharifi, E. (2021). Evaluation of satellite/reanalysis precipitation products over Iran. *International Journal of*

Remote Sensing, *42*(9), 3474-3497. https://doi.org/10.1080/01431161.2021.1875508

Tavares, M. H., Cunha, A. H. F., Motta-Marques, D., Ruhoff, A. L., Cavalcanti, J. R., Fragoso, C. R., Martín Bravo, J., Munar, A. M., Fan, F. M., & Rodrigues, L. H. R. (2019). Comparison of Methods to Estimate Lake-Surface-Water Temperature Using Landsat 7 ETM+ and MODIS Imagery: Case Study of a Large Shallow Subtropical Lake in Southern Brazil. *Water*, *11*(1), Article 1. https://doi.org/10.3390/w11010168

Tedesco, A. M., López-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Pérez-Hämmerle, K.-V., Brancalion, P. H. S., Wilson, K. A., Oliveira, M., Correa, D. F., Ota, L., Morrison, T. H., Possingham, H. P., Mills, M., Santos, F. C., & Dean, A. J. (2023). Beyond ecology: Ecosystem restoration as a process for social-ecological transformation. *Trends in Ecology & Evolution*, *38*(7), 643-653. https://doi.org/10.1016/j.tree.2023.02.007

Tierney, G. L., Faber-Langendoen, D., Mitchell, B. R., Shriver, W. G., & Gibbs, J. P. (2009). Monitoring and evaluating the ecological integrity of forest ecosystems. *Frontiers in Ecology and the Environment*, *7*(6), 308-316. https://doi.org/10.1890/070176

Tilgenkamp, A. (2025, agosto 2). *Theil–Sen estimator [online]. MATLAB Central File Exchange.* https://www.mathworks.com/matlabcentral/fileexchange/34308-theil-sen-estimator

Torres, R. (2023, enero 24). Resistance In Chile's "State Of Exception". *Majority Post*. https://majoritypost.com/resistance-in-chiles-state-of-exception/

Torres, R., Azócar, G., Gallardo, R., & Mendoza, J. (2022). *Water Extractivism and Decolonial Struggles in Mapuche Territory, Chile*. *15*(1).

Torres, R., Azócar, G., Rojas, J., Montecinos, A., & Paredes, P. (2015). Vulnerability and resistance to neoliberal environmental changes: An assessment of agriculture and forestry in the Biobio region of Chile (1974–2014). *Geoforum*, *60*, 107-122. https://doi.org/10.1016/j.geoforum.2014.12.013

Traganos, D., Poursanidis, D., Aggarwal, B., Chrysoulakis, N., & Reinartz, P. (2018). Estimating Satellite-Derived Bathymetry (SDB) with the Google Earth Engine and Sentinel-2. *Remote Sensing*, *10*(6), Article 6. https://doi.org/10.3390/rs10060859

Trenberth, K. E., & Hoar, T. J. (1996). The 1990–1995 El Niño-Southern Oscillation Event: Longest on Record. *Geophysical Research Letters*, *23*(1), 57-60. https://doi.org/10.1029/95GL03602

Troitskaya, Y., Rybushkina, G., Soustova, I., Balandina, G., Lebedev, S., & Kostianoy, A. (2012). Adaptive retracking of Jason-1 altimetry data for inland waters: The example of the Gorky Reservoir. *International Journal of Remote Sensing*, *33*(23), 7559-7578. https://doi.org/10.1080/01431161.2012.685972

UCM. (2024). *Earth Engine Data Catalog: TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces [online]. Merced, University of California Merced.* https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE#bands

University of North Carolina. (2025). *Mediciones en Lagos Red Ciudadana y Satelital*. LOCSS. https://www.locss.org/es

Upreti, G. (2023). Autopoiesis, Organizational Complexity, and Ecosystem Health. En G. Upreti (Ed.), *Ecosociocentrism: The Earth First Paradigm for Sustainable*

Living (pp. 91-110). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-41754-2_5

Urrutia, R., Almanza, V., & Woelfl, S. (2022, septiembre 8). *Seminario proyecto: Levantamiento de información limnológica para la propuesta de NSCA de lagos nor-patagónicos* [[Discurso principal]. Seminario en línea.].

US EPA. (2011). *National wetland condition assessment: Field operations manual*.

US EPA. (2025). *Factsheets on Water Quality Parameters*. https://www.epa.gov/awma/factsheets-water-quality-parameters

US EPA, O. (2015, abril 16). *What is the National Lakes Assessment?* [Overviews and Factsheets]. https://www.epa.gov/national-aquatic-resource-surveys/what-national-lakes-assessment

USGS. (2025). *U.S. Geological Survey*. https://www.usgs.gov/

Valdés-Pineda, R., Cañón, J., & Valdés, J. B. (2018). Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals. *Journal of Hydrology*, *556*, 1153-1170. https://doi.org/10.1016/j.jhydrol.2017.01.031

Valdés-Pineda, R., Valdés, J. B., Diaz, H. F., & Pizarro-Tapia, R. (2016, junio 30). *Analysis of spatio-temporal changes in annual and seasonal precipitation variability in South America-Chile and related ocean-atmosphere circulation patterns.* | *EBSCOhost*. https://doi.org/10.1002/joc.4532

Vela, S. R. (2019). Método mayéutica y consultorías filosóficas en el siglo XXI. *Phainomenon*, *18*(2), 141-154. https://doi.org/10.33539/phai.v18i2.1745

Vera, R., & Rosner, C. (2020). *Recopilación y análisis de antecedentes para la revisión de la Norma Secundaria de Calidad Ambiental del lago Llanquihue*. ResearchGate. https://doi.org/10.13140/RG.2.2.29431.80801

Vergara Díaz, G., Vázquez, V. S., & Herrera Machuca, M. Á. (2018). Análisis del ambio temporal y espacial del uso del suelo en la región Centro-sur de Chile. *Ciência Florestal*, *28*, 1831-1844. https://www.scielo.br/j/cflo/a/rtg7y6cGShDvQkMjWL7k47Q/?lang=es&format=html&stop=next

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). *A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index*. https://doi.org/10.1175/2009JCLI2909.1

Vlasova, T., Petrov, A. N., & Volkov, S. (2021). Rethinking Sustainability Monitoring in the Arctic by Linking Resilience and Sustainable Development in Socially-Oriented Observations: A Perspective. *Sustainability*, *13*(1), Article 1. https://doi.org/10.3390/su13010177

Voulvoulis, N., Giakoumis, T., Hunt, C., Kioupi, V., Petrou, N., Souliotis, I., Vaghela, C., & binti Wan Rosely, WIH. (2022). Systems thinking as a paradigm shift for sustainability transformation. *Global Environmental Change*, *75*, 102544. https://www.sciencedirect.com/science/article/pii/S0959378022000826

Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., & Bierkens, M. F. P. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, *37*(20). https://doi.org/10.1029/2010GL044571

Wadoux, A. M. J.-C., & Minasny, B. (2024). Some limitations of the concordance correlation coefficient to characterise model accuracy. *Ecological Informatics*, *83*, 102820. https://doi.org/10.1016/j.ecoinf.2024.102820

Wakana, I., Kadono, Y., Urabe, J., Tamura, Y., Suzuki, Y., Yamada, H., Oyama, Y., Wada, K., Hasegawa, T., & Ohara, M. (2023). Varying stages of ecological succession in lakes subdivided by volcanic eruptions at Akan Caldera, Japan. *Hydrobiologia*, *850*(18), 3919-3933. https://doi.org/10.1007/s10750-023-05231-5

Wang, H., Qi, Y., Lian, X., Zhang, J., Yang, R., & Zhang, M. (2022). Effects of climate change and land use/cover change on the volume of the Qinghai Lake in China. *Journal of Arid Land*, *14*(3), 245-261. https://doi.org/10.1007/s40333-022-0062-4

Warner, S., Blanco Ramírez, S., de Vries, S., Marangu, N., Ateba Bessa, H., Toranzo, C., Imaralieva, M., Abrate, T., Kiminta, E., Castro, J., de Souza, M. L., Ghaffar Memon, A., Loiselle, S., & Juanah, M. S. E. (2024). Empowering citizen scientists to improve water quality: From monitoring to action. *Frontiers in Water*, *6*. https://doi.org/10.3389/frwa.2024.1367198

Westra, L., & Lemons, J. (2012). *Perspectives on Ecological Integrity*. Springer Science & Business Media.

Wetzel, R. G. (2001). *Limnology: Lake and River Ecosystems*. Gulf Professional Publishing.

Williams, J. (2021). *Climate change is racist: Race, privilege and the struggle for climate justice*. Icon Books. https://books.google.es/books?hl=es&lr=&id=RIQiEAAAQBAJ&oi=fnd&pg=PP8&dq=Williams,+J.+(2021).+Climate+change+is+racist:+Race,+privilege+and+the+struggle+for+climate+justice.+Icon+Books.&ots=NWw2BQCCgc&sig=7BuVe4PrQpNz7d1MptUcKTYDbj4

Willmott, C. J. (1981). On the Validation of Models. *Physical Geography*, *2*(2), 184-194. https://doi.org/10.1080/02723646.1981.10642213

Winkler, K., Fuchs, R., Rounsevell, M., & Herold, M. (2021). Global land use changes are four times greater than previously estimated. *Nature Communications*, *12*(1), 2501. https://www.nature.com/articles/s41467-021-22702-2

Winter, T. C. (1981). Uncertainties in Estimating the Water Balance of Lakes. *JAWRA Journal of the American Water Resources Association*, *17*(1), 82-115. https://doi.org/10.1111/j.1752-1688.1981.tb02593.x

WISDOM. (2025). *Objectives of the WISDOM Project*. https://wisdom.eoc.dlr.de/en/content/objectives-wisdom-project.html

WMO. (2025). *WMO Information System (WIS)*. https://old.wmo.int/extranet/pages/prog/www/WIS/

WMOa. (2025). *Observing Systems Capability Analysis and Review Tool (OSCAR)*. https://oscar.wmo.int/surface/#/

Wolodarsky-Franke, A., & Díaz, S. (2011). Cordillera de Nahuelbuta. *Reserva Mundial de Biodiversidad. Valdivia, Chile: WWF*.

Wongchuig, S., Carlo Espinoza, J., Condom, T., Junquas, C., Sierra, J. P., Fita, L., Sörensson, A., & Polcher, J. (2023). Changes in the surface and atmospheric water budget due to projected Amazon deforestation: Lessons from a fully coupled model simulation. *Journal of Hydrology*, *625*, 130082. https://doi.org/10.1016/j.jhydrol.2023.130082

Woods, S. (2025). How citizen science can help to solve the global freshwater crisis. *Nature*, *644*(8077), 582-582. https://doi.org/10.1038/d41586-025-02614-7

Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews*

Earth & Environment, *1*(8), 388-403. https://doi.org/10.1038/s43017-020-0067-5

Woolway, R. I., Sharma, S., & Smol, J. P. (2022). Lakes in Hot Water: The Impacts of a Changing Climate on Aquatic Ecosystems. *BioScience*, *72*(11), 1050-1061. https://doi.org/10.1093/biosci/biac052

Woolway, R. I., Tong, Y., Feng, L., Zhao, G., Dinh, D. A., Shi, H., Zhang, Y., & Shi, K. (2024). Multivariate extremes in lakes. *Nature Communications*, *15*(1), 4559. https://doi.org/10.1038/s41467-024-49012-7

Wu, J., Li, W., Du, H., Wan, Y., Yang, S., & Xiao, Y. (2025). Nonlinear responses of coupled socioecological systems to land use and climate changes in the Yangtze river basin. *Scientific Reports*, *15*(1), 6940. https://doi.org/10.1038/s41598-025-92084-8

Wurtsbaugh, W. A., Paerl, H. W., & Dodds, W. K. (2019). Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *WIREs Water*, *6*(5), e1373. https://doi.org/10.1002/wat2.1373

Xu, J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Xu, W. (2022). Ecological Integrity Evaluation of Organically Evolved Cultural Landscape. *Mobile Information Systems*, *2022*(1), 9554359. https://doi.org/10.1155/2022/9554359

Xu (徐菊英), J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Yang, J., & Du, X. (2017). An enhanced water index in extracting water bodies from Landsat TM imagery. *Annals of GIS*, *23*(3), 141-148. https://doi.org/10.1080/19475683.2017.1340339

Yang, Xu, M., Li, R., Zhang, L., & Deng, Q. (2020). Estimating the ecological water levels of shallow lakes: A case study in Tangxun Lake, China. *Scientific Reports*, *10*(1), 5637. https://doi.org/10.1038/s41598-020-62454-5

Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J.-F., Wada, Y., & Berge-Nguyen, M. (2023). Satellites reveal widespread decline in global lake water storage. *Science*, *380*(6646), 743-749. https://doi.org/10.1126/science.abo2812

Zelený, J., Mercado-Bettín, D., & Müller, F. (2021). Towards the evaluation of regional ecosystem integrity using NDVI, brightness temperature and surface heterogeneity. *Science of The Total Environment*, *796*, 148994. https://www.sciencedirect.com/science/article/pii/S0048969721040663

Zhang, M., Lee, H., SHUM, C. K., Alsdorf, D., Schwartz, F., Tseng, K.-H., Yi, Y., Kuo, C.-Y., Tseng, H.-Z., Braun, A., Calmant, S., Filizola, N., & Seyler, F. (2010). Application of retracked satellite altimetry for inland hydrologic studies. *International Journal of Remote Sensing*, *31*(14), 3913-3929. https://doi.org/10.1080/01431161.2010.483495

Zhao, G., Li, Y., Zhou, L., & Gao, H. (2022). Evaporative water loss of 1.42 million global lakes. *Nature Communications*, *13*(1), 3686. https://doi.org/10.1038/s41467-022-31125-6

Zhao, Y., Feng, D., Yu, L., Wang, X., Chen, Y., Bai, Y., Hernández, H. J., Galleguillos, M., Estades, C., Biging, G. S., Radke, J. D., & Gong, P. (2016). Detailed dynamic land cover mapping of Chile: Accuracy improvement by integrating multi-temporal data. *Remote Sensing of Environment*, *183*, 170-185. https://www.sciencedirect.com/science/article/pii/S0034425716302188

Zhou, J., Leavitt, P. R., Rose, K. C., Wang, X., Zhang, Y., Shi, K., & Qin, B. (2023). Controls of thermal response of temperate lakes to atmospheric warming. *Nature Communications*, *14*(1), 6503. https://doi.org/10.1038/s41467-023-42262-x

Zhu, J., Peng, S., Shen, X., Lin, Z., Gong, L., Zhang, R., & Huang, B. (2024). Multiple scale impacts of land use intensity on water quality in the Chishui river source area. *Ecological Indicators*, *166*, 112396. https://doi.org/10.1016/j.ecolind.2024.112396

Zhu, L., Ju, J., Qiao, B., Liu, C., Wang, J., Yang, R., Ma, Q., Guo, L., & Pang, S. (2025). Physical and biogeochemical responses of Tibetan Plateau lakes to climate change. *Nature Reviews Earth & Environment*, *6*(4), 284-298. https://doi.org/10.1038/s43017-025-00650-5

Capítulo IV

Thermal patterns in a warm monomictic lake using advanced 3D hydrodynamic modeling

Abstract

We applied the advanced 3D model COHERENS to Lake Lanalhue (LL), Chile, to describe spatial and temporal patterns of lake water temperature (LWT) from 2001 to 2024. The model is forced with hourly-ERA5 meteorological data and initialized with a measured in-situ temperature profile on a 100 m resolution bathymetry. Validation is performed using in-situ and satellite (Landsat 8) LWT datasets. Long-term patterns are analyzed through climatologies and domain averages. Despite the coarse resolution of meteorological forcing, validation against in-situ data demonstrates the model's ability to reproduce the annual cycle of LWT in LL (R^2: 0.69–0.97; d: 0.88–0.98; NRMSE: 0.12–0.23). Satellite validation shows R^2 = 0.91, NRMSE = 0.10, d = 0.97, and up to 1°C bias, excepting winter. The lake warmed by ~0.12 °C per decade, with interannual variability modulated by the El Niño-Southern Oscillation. This highlights the

potential of 3D modelling to represent the thermo-hydrodynamics of medium-sized lakes in data scarce environments.

Keywords: 3D modeling, COHERENS, Lake modeling, Lake Water Temperature, Lanalhue Chile, Landsat.

1. Introduction

The vertical thermal structure in lakes modulates a wide range of physical and biogeochemical processes, including nutrient cycling, oxygen distribution, and ecosystem dynamics (Zhou et al., 2023). Recent studies have suggested that lakes worldwide are undergoing rapid and often abrupt changes in water temperature, ice cover, water quality, and hydrobiological conditions as a result of ongoing climate change (Meerhoff et al., 2022; Piccolroaz et al., 2024a; Woolway et al., 2022). These changes are particularly acute in regions with high climatic sensitivity, but limited observational data and modeling experience complicates both diagnosis and management. In this context, lake modeling has emerged as a critical tool to generate long term three dimensional data and use them to understand the thermodynamics of the lakes. Although some hydrodynamic simulations of lakes have been conducted in recent years, the field remains relatively new, especially in the Southern Hemisphere. South America remains largely underrepresented in most global lake modeling studies (M. Guo et al., 2021).

There are several processes that a model simulates to represent the thermal patterns of a lake. Surface thermodynamics, wind, and inflow dynamics provide energy sources for the hydrodynamical processes inside the lake, such as transport, turbulent kinetic energy (TKE), internal waves and mixing (M. Guo et al., 2021; Hodges et al., 2000; Jerlov, 1968). There are three main components that modulate the surface heat exchange: the outgoing longwave radiation, the incoming longwave radiation from the atmosphere and the incoming shortwave radiation from the sun (Schmid & Read, 2022). There are also other components in the heat budget: the outgoing latent heat through evaporation, the outgoing sensible heat and the incoming and outcoming advected energy through inflows and outflows. Finally, there is a heat exchange with the bottom (Schmid & Read, 2022), which becomes important only for shallow lakes (up to 5 m depth) (X. Fang & Stefan, 1996).

Theory-based models offer a means to simulate these fundamental processes that govern lake water temperature (LWT). However, modeling stratified systems introduce specific challenges, such as numerical diffusion and difficulties maintaining long-term simulation accuracy (Hodges et al., 2000). One-dimensional (1D) models, which resolve vertical processes and assume horizontal homogeneity, are widely used due to their simplicity and low computational requirements (Ishikawa et al., 2022), making them suitable for long-term analysis. Examples include DYRESM (Imberger & Patterson,

1989), GLM (Hipsey et al., 2019), FLAKE (Mironov et al., 2005) and MyLake (Saloranta & Andersen, 2007). However, 1D models cannot capture certain three-dimensional (3D) phenomena. Most water bodies present a complex morphology, whose effects on the hydrodynamics can only be taken into account by 3D models (Piccioni et al., 2021). These types of models are commonly developed for marine applications and adapted to lakes in several studies (Afsharian & Taylor, 2019; Baracchini et al., 2020; Nekouee et al., 2015). Some examples of 3D models are POM (Mellor, 1988), Delft3D-FLOW (Deltares, 2025) and COHERENS (Luyten, 2025). 3D models provide higher spatial resolution and often show better agreement with observations, but they require substantially more computational resources (Ishikawa et al., 2022; Stepanenko et al., 2010). These types of models are commonly developed for marine applications and adapted to lakes in several studies (Afsharian & Taylor, 2019; Baracchini et al., 2020; Nekouee et al., 2015). However, to the best of our knowledge, most of the studies are centered in big lakes. Only a few studies apply 3D modelling to medium-to-small-sized lakes (Hosseini-Sadabadi et al., 2023; Marinov et al., 2006; Piccioni et al., 2021).

In this study, we focus on Lake Lanalhue, a medium-sized, monomictic (that means experiencing one mixing event per year) and eutrophic lake in central-Chile, which has been affected by anthropogenic and natural pressures (Alaniz et al., 2021; O. Parra, 2003b). Located in a region influenced by El Niño-Southern Oscillation (ENSO) events (detailed in Section 2.) (Garreaud,

2009; Garreaud et al., 2020; Montecinos & Aceituno, 2003; Rutllant & Fuenzalida, 1991), the lake exhibits stratified thermal regimes that may modulate local ecological dynamics. Previous studies conducted in south-central-Chile on lake variability have documented harmful algal blooms and signs of eutrophication (Abarzúa et al., 2020; Almanza et al., 2016; Ascencio et al., 2018), reinforcing the need for long-term thermal characterization as a foundation for water quality prediction.

To address this gap, the aim of this study is to represent the thermal structure of Lake Lanalhue using the advanced hydrodynamic model COHERENS (Luyten, 2025). We conducted a long-term 24-year (2001–2024) model simulation to analyze the spatial and temporal LWT patterns. The COHERENS model is configured with 100 m resolution bathymetry with 10 vertical levels on sigma coordinate, forced with hourly ERA5 atmospheric reanalysis data, and a single in-situ LWT profile as the initial condition. The model simulation is validated using both in-situ and satellite-derived (Landsat 8) LWT data. The model performance regarding LWT is evaluated using R^2, normalized root mean square error *(NRMSE*), and Willmott's index (*d*) (Willmott, 1981), offering a rigorous test of the model robustness. In regions with limited observational data, validated model outputs are really relevant. The long-term simulation is used to examine seasonal stratification cycles and interannual thermal anomalies potentially linked to ENSO variability. In doing so, the study contributes to filling a significant gap in 3D lake modeling efforts

in the Southern Hemisphere, especially in the context of lakes facing stress from climate change and eutrophication.

COHERENS is a 3D finite-difference, multi-purpose numerical model designed for coastal and shelf seas. It can be coupled with biological, sediment dynamics, contaminant and particle transport modules and can resolve mesoscale to seasonal scale processes (Luyten, 2025). Previous studies have adapted COHERENS for other lakes and semi-enclosed bays (Afsharian & Taylor, 2019; Amour & Kauranne, 2017; Huttula & Liukko, 2014; Mano et al., 2015; Mano & Shuku, 2014). However, in this study, we emphasize the novelty of our application in three aspects: i) application to a medium-sized lake, rarely covered in 3D modeling literature; ii) implementation of a case-specific physical parameterization, such as the surface heat budget and vertical heat transfer; and iii) use of global, open-access and relatively coarse (~28 km) hourly ERA5 reanalysis data as meteorological forcing, enhancing reproducibility in data-scarce environments.

This approach follows precedents that use global medium-to-coarse resolution datasets to successfully simulate basin-scale processes. Examples such as Betts et al. (2020), Bongioannini Cerlini et al. (2022), Frassl et al. (2018), Lin et al. (2022) or Pedreros-Guarda et al. (2025), that use 9-to-80 km to reproduce variables such as lake water levels and LWT, including seasonal stratification patterns, confirming the strong potential of this methodology for representing key lake processes.

By applying COHERENS under realistic data constraints, this study offers a reproducible thermal modeling framework for similar under-monitored lakes in climatically sensitive regions. The results lay the groundwork for future work integrating biogeochemical modules, improving forecasts of algal blooms, and advancing lake management under changing environmental conditions.

2. Study area

The study area is Lake Lanalhue and its basin, located in the Biobío region of central-Chile, near the Pacific Ocean (Figure IV.1). This region is characterized by a warm-temperate main climate with a warm and dry summer (Kottek et al., 2006; Sarricolea et al., 2017) and precipitations concentrated in winter (Bravo Orrego, 2018).

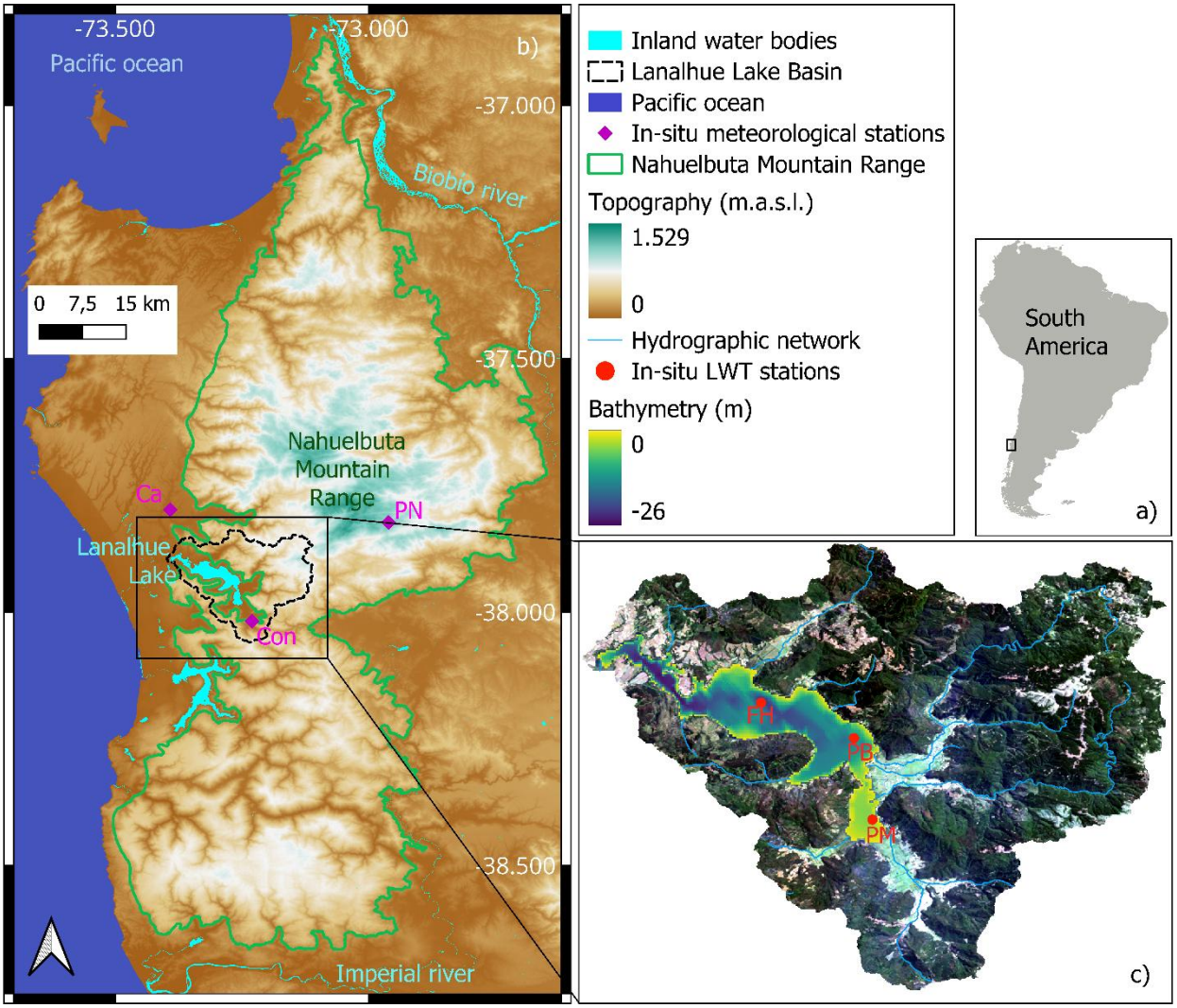


Figure IV.1. Study area. a) Location in South America. b) Topography of the area surrounding Lake Lanalhue and position of in-situ meteorological stations: Cañete (Ca), Contulmo (Con) and Parque Nahuelbuta (PN). c) RGB Composite of the Lake Lanalhue basin showing: i) in-situ lake water temperature (LWT) stations (Puerto Peleco (PP), Frente Hostería (FH), Puerto Manzano (PM)) and ii) Bathymetry of Lake Lanalhue, Chile.

In central-Chile (30°S - 41°S), most precipitation originates from cold fronts associated with migratory low-pressure systems embedded in the mid-latitude westerlies (Rutllant & Fuenzalida, 1991). The penetration of these cold

fronts, the local temperatures and winds are all modulated by the subtropical anticyclone in the southeastern Pacific (Montecinos & Aceituno, 2003; Sobarzo et al., 1997), which itself is influenced by the ENSO (Barría et al., 2021; Garreaud, 2009). ENSO significantly affects both interannual and winter precipitation and temperature variability in the region (Quintana & Aceituno, 2012; Rutllant & Fuenzalida, 1991; Valdés-Pineda et al., 2016). El Niño years in central-Chile are typically characterized by warmer winters and colder late springs compared to La Niña years (Hernandez et al., 2022).

The region has experienced significant climatic stress over the past years. Central-Chile has been severely affected by the ongoing Megadrought, which began in 2010 and has resulted in a 25% to 45% reduction in precipitation (Garreaud et al., 2020). Despite the rise of air temperatures is low or even negative in some regions of central-Chile (Falvey & Garreaud, 2009), the climatic projections expect a rising of temperature for the region in the future (Salazar et al., 2024). Since the mid-20th, ERA5 reanalysis shows an increase in evaporation trend in Lanalhue Lake (Pedreros-Guarda et al., 2025).

Locally, precipitation is modulated by the Nahuelbuta Mountain Range (whose altitude is up to 1500 meters above sea level (m.a.s.l.), Figure 1), which acts as a natural climatic barrier (Bravo Orrego, 2018). As a result, the western slope receives more rainfall than the eastern side, which is reflected in the

abundance of water with the presence of numerous rivers, lakes, lagoons and wetlands in the region (Huenupil-Marihuen. et al., 2010).

The Lake Lanalhue Basin, like all Nahuelbutan lake basins, follows a pluvial alimentation regime, meaning that the main feeding comes from direct precipitation and surface runoff. The lake has no large tributary rivers; rather, it is fed by diffuse surface runoff from numerous small and intermittent streams draining the surrounding slopes and lowlands (Pedreros-Guarda et al., 2025). This suggests that precipitation (and diffuse runoff) and evaporation are crucial in modulating the lake's water balance, rather than specific water courses.

Lake Lanalhue receives an average annual rainfall of 2300 mm (O. Parra et al., 1999; O. Parra, 2003b). It is part of a group of small, exorheic (that is, water flows out to an external water body such as the sea, a lake or a river) coastal basins that drain the western slope of the Nahuelbuta Mountain Range, known collectively as the Nahuelbutan lakes. These lentic systems share similar climatic and geological characteristics and do not experience winter ice cover (O. Parra, 2003b).

Lake Lanalhue has a maximum length of 9.6 km, a width of 4.3 km, and a maximum depth of 26 m. The surface area of the lake is 31.9 km², and its drainage basin covers 327.43 km². The lake lies 12 meters above sea level and has a water residence time of 12.5 months. It undergoes thermal stratification in summer (O. Parra et al., 1999; O. Parra, 2003b; O. Parra et al.,

2005a). Classified as an eutrophic lake, it has experienced increasingly frequent algal blooms in recent years (Almanza et al., 2016). Additional key physical, ecological and environmental characteristics of Lake Lanalhue are summarized in Table IV.1.

Table IV.1. Main physical, ecological and environmental characteristics of Lake Lanalhue (Almanza et al., 2016; O. Parra et al., 1999; O. Parra, 2003b; O. Parra et al., 2005a).

Characteristic	**Description/value**
Lake area (km²)	31.9
Basin area (km²)	327.43
(Basin area / lake area) ratio	10.2
Máx length (km)	9.6
Máx width (km)	4.3
Average depth (m)	13.1
Máx depth (m)	26
Perimeter (km)	58.6
Precipitation (mm/year)	2300
Height (m.a.s.l.)	12
Renovation time (months)	12.5
Trophic degree	Eutrophic
Seasonal stratification	Yes
Main watershed use	Forestry, recreational, tourism, residential and agriculture.
Main lake use	Recreational, Tourism, Receptor
Algal bloom	Yes
Direct tributaries	11
Type of basin	Coastal, dendritic, exorheic
Alimentation	Pluvial
Hydrodynamic type	Monomictic

3. Data and Methods

3.1. Data

The COHERENS model (ECOMOD, 2025) is forced with ERA5 hourly meteorological reanalysis (ERA5) on the open surface boundary, and Initial condition is based on in-situ LWT profile. The bathymetry data is used as the bottom boundary condition. The model validation is performed using both in-situ LWT profiles and Landsat 8 satellite imagery. Detailed descriptions of these datasets are provided in Sections 3.1.1. to 3.1.4. and summarized in Table IV.2.

Table IV.2. Summary of the datasets used to force, initialise and validate the model COHERENS.

Dataset	**Variables/Description (unit)**		**Period**	**Frequency**	**Spatial resolution**
ERA5[a]	10m u- and v-components of neutral wind (m s^{-1}), surface atmospheric pressure (Pa), 2m dew point temperature (K), total cloud cover (dimensionless), mean total precipitation and evaporation rates (mm s^{-1})		1940 - present	Hourly and daily	31 km
In-situ meteorolo-gical stations[c]	Precipitation (mm) at 78 meters above sea level (m.a.s.l.).	Cañete [DGA]	1979 - 2020	Daily	Punctual data
	Air temperature (ºC) and	Contulmo [DGA]	1994 - 2019		

	precipitation (mm) at 41 and 1117 m.a.s.l., respectively	Parque Nahuelbuta [DGA]	2002 - 2019		
In-situ temperature profiles[d]	Lake temperature (ºC) profiles at 0-0.5 m (surface), 0.5-5m, 5-10m, ＞10m (bottom).		2000 - 2010	Seasonally	Punctual stations
Bathymetry[e]	Depth (m)		Data collected on 22/3/2019		100 m

[a]Hersbach, (2023). [b]Alvial Vásquez et al. (2020). [c](CR)2, (2025). [d]DGA (2025). [e]Provider: EULA-Chile.

3.1.1. Meteorological datasets

3.1.1.1. ERA5 datasets

The primary forcing for the model COHERENS is the ERA5 hourly reanalysis dataset (Hersbach, 2023). The model is run in its non-flux configuration (Luyten, 2025), which requires the following meteorological variables: 10 m u- and v-components of wind (*u10, v10*), mean sea level pressure (*msl*), surface atmospheric pressure (*sp*), relative humidity (*RH*), 2 m air- temperature (*t2m*), total cloud cover (*tcc*) and mean total precipitation rate (*tpr*). Relative humidity is calculated based on 2 m dew point temperature (*d2m*) and t2m.

ERA5 is a global reanalysis product produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), with a horizontal resolution of 0.25°, equivalent to approximately 27.8 km at the local latitude. For this

study, a 13 x 13 grid surrounding Lake Lanalhue was extracted. ERA5 combines model output with a wide range of observations from WMO Information System (WIS) (WMO, 2025) using data assimilation techniques, relying on a coupled atmospheric and land-surface model HTESSEL (Balsamo et al., 2009).

3.1.1.2. In-situ meteorological stations

Data from three in-situ meteorological stations: Cañete (Ca), Contulmo (Con) and Parque Nahuelbuta (PN), were obtained from the CR(2) Explorer platform ((CR)2, 2025). All three stations provide daily *tp (mm)*, while the Contulmo and Parque Nahuelbuta stations also provide daily minimum and maximum air temperature (°C). For this study, air temperature is assumed equivalent to t2m. The locations of these stations are shown in Figure 1b. There are many Chilean in-situ meteorological stations that are used to feed ERA5 reanalysis, as they form part of the WMO WIS (ECMWF, 2025). However, ERA5 is completely independent from these three in-situ meteorological stations (WMOa, 2025).

3.1.2. Bathymetry

The bathymetry used in this modelling study was surveyed by EULA-Chile, University of Concepción, in 2008. This dataset is interpolated onto a 145 x 105 grid with 100 m resolution (Figure IV.1), providing a detailed representation of the lake bottom necessary for hydrodynamic modeling. To

represent the lake in the model, a cartesian uniform rectangular 3D-grid is used, with dimensions of: 145 (x-axis), 105 (y-axis) and 10 (z-axis).

3.1.3. In-situ lake water temperature (LWT)

The model COHERENS is initialized using a single vertical in-situ LWT profile and validated using a broader dataset of in-situ LWT observations. These temperature profiles are provided by the General Directorate of Waters (DGA), Chile's national water agency. Original measurements were taken at five stations: Puerto Peleco (PP), Frente Hostería (FH), Playa Blanca (PB), Sector Centro (SC), Puerto Manzano (PM). Two stations (SC and PP) are excluded: SC due to insufficient data, and PP because its location near the shoreline introduces edge effects that the model cannot adequately resolve. Although PM lacks measurements near the lake bottom, it is retained in the analysis. Therefore, the LWT stations used for the analysis are FH, PB and PM (Figure IV.1c, Table IV.3). Measurements were taken at varying times of the day (between 9:00 and 21:00 local time, UTC-4) and cover all seasons with irregular sampling frequency. The initial condition for the model is set using the vertical temperature profile from 6/11/2001 at FH station, while data collected from this and the other two stations in different periods are used for the model validation. This location is selected because it is the deepest in-situ station, thus, it would represent the most developed stratified condition and probably the closest to reality. The dataset starts from the year 2000 and this particular

profile is selected because it represents the earliest complete, stratified vertical thermal structure of the lake.

Table IV.3. Coordinates of LWT and meteorological stations used. LWT stations: Frente Hostería (FH), Playa Blanca (PB), Puerto Manzano (PM). Meteorological stations: Cañete (Ca), Contulmo (Con), Parque Nahuelbuta (PN).

Station	Coordinates
FH	-37.9173, -73.3105
PB	-37.9348, -73.2646
PM	-37.975, -73.2555

3.1.4. Landsat 8 Satellite Imagery

Landsat 8 satellite imagery is provided by the United States Geological Survey (USGS) and accessed via the Google Earth Engine (GEE) platform. The code to extract the images can be seen at Pedreros-Guarda (2025). For this study, we used the dataset USGS Landsat 8 Level 2, Collection 2, Tier 1 (EEDC, 2025a). The Landsat satellites overpass the study area at approximately 10:40 local time (UTC-4), as indicated in the metadata of each image.

This dataset includes atmospherically corrected land surface temperature (LST) derived from the Thermal Infrared Sensor (TIRS) aboard Landsat 8. The imagery contains one thermal infrared (TIR) band, which is processed to orthorectified surface temperature. Additionally, intermediate

bands used in LST product generation and quality assurance (QA) bands are included (EROS, 2022). The surface reflectance (SR) products are generated using the Land Surface Reflectance Code (LaSRC). The LST products are derived using a single-channel algorithm developed collaboratively by the Rochester Institute of Technology (RIT) and National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) (EROS, 2022).

The Image Collection spans from 11th of February 2013, to the present, with this study focusing on the period 5th of May 2013 – 13th of December 2024. Images were filtered to retain only those with cloud cover < 30%, and pixels flagged as low-quality pixels in the QA bands were removed from the analysis. To isolate the lake area, we applied a lake mask generated from the COHERENS model output. Additionally, pixels at the land-water interface were removed using the Modified Normalized Difference Water Index (MNDWI), as proposed by (Yang & Du, 2017).

Following all filtering steps, 129 usable images were retained out of the 241 initially available in GEE. The number of valid images per year varied between six (2017) and sixteen (2015). Seasonally, December to February (austral summer) typically yielded 2 to 6 usable images per month, while June to August (austral winter) yielded only 1 to 4 images per month due to increased cloud cover and atmospheric disturbances.

3.1.5. Oceanic Niño Index

The ENSO is a major ocean-atmosphere phenomenon centered in the equatorial Pacific Ocean, and is a key driver of interannual climate variability. In this study, ENSO is analyzed in relation to the interannual variability of LWT simulated by the COHERENS model. Among the various indices used to characterize ENSO, the Oceanic Niño Index (ONI) is widely accepted as a standard metric, particularly for studies focused on South America. The ONI is calculated as a 3-month running mean of sea surface temperature in the Niño 3.4 region (5°N-5°S, 170°W-120°W), based on NOAA's SST reconstruction. ENSO events are typically defined when the ONI exceeds +0.5°C (El Niño) or drops below -0.5°C (La Niña) for at least 5 consecutive overlapping 3-month periods (NOAA, 2024a). For this study, ONI data from 1950 to the present were obtained from the NOAA Climate Prediction Center. The ONI is particularly relevant for this region, as SST anomalies in the Niño 3.4 region strongly influence climatic conditions in South America, including precipitation and temperature variability across central-Chile (Merryfield & Lee, 2023; Trenberth & Hoar, 1996; J. Xu et al., 2025).

We will use the ONI to confirm the relationship of ENSO with temperature reported by Hernandez et al. (2022), that El Niño years in central-Chile are typically characterized by warmer winters and colder late springs compared to La Niña years. We will compare winters and late springs in years La Niña (2007, 2008, 2010, 2011, 2017) against years El Niño (2002, 2004,

2006, 2009, 2015) and neutral years (2001, 2003, 2005, 2012, 2013, 2014, 2016, 2018).

3.2. Hydrodynamic modelling

In this section, we describe the methods used to set up the model and conduct the validation procedure.

3.2.1. Model setup

3.2.1.1. Surface boundary conditions

We selected the schemes of Clark et al. (1974) for outgoing long-wave radiation and the Shine (1984) for incoming short-wave radiation (ISWR). We selected the default Neumann surface boundary condition for temperature, which is using the model's surface heat flux formulations. The optical module is enabled through attenuation coefficients, which is related to the optical properties of the water and defines the penetration of the ISWR (Jerlov, 1968; Mortimer, 1974). As water clarity is included by optical coefficients (λ_1, λ_2, R), we have selected: $\lambda_1 = 10$ (default), $\lambda_2 = 1$ (non-default) and $R = 0.54$ (default).

3.2.1.2. Discharge

In this application, we have not included discharges, assuming that their contribution to LWT is minor compared to the rest of the parametrizations

mentioned. This is justified by the fact that the incoming flows are not rivers, but small streams (see Section 2.). Besides that, heat transfer by convection is not included in COHERENS, since it is a hydrostatic model. So even if we included this component, its effect in LWT may not be well represented. However, in future, measuring the discharge with a flowmeter and applying a non-hydrostatic model would be interesting to study the impact of such discharges in the thermodynamics of LWT.

3.2.1.3. Other parametrizations

Several physical processes within the lake domain are parametrized in this application. As there is no marine intrusion, salinity is set to zero and tidal forcing is disabled. For density calculations, we use the general equation of state from McDougall et al. (2003), with variable density. The baroclinic pressure gradient is discretized using the Shchepetkin & McWilliams (2003) algorithm, as implemented in COHERENS (Luyten, 2025). The bottom drag coefficient is parameterized using a spatially uniform roughness length of 0.5 m, with a quadratic bottom stress formulation. Vertical diffusion is modeled using an algebraic scheme based on the Munk-Anderson formulation, which departs from the default parametrization. For horizontal diffusion, we apply Smagorinsky (1963) formulation. Atmospheric stratification is enabled through the Monin-Obukhov similarity theory, with neutral surface drag and exchange coefficients computed using the Kondo (1975) equations.

The complete parametrization can be found at Pedreros-Guarda (2025).

3.2.2. Model validation

3.2.2.1. Validation with in-situ data

Model validation is first performed using interpolated in-situ LWT profiles across 10 vertical levels. The comparison between the COHERENS output and the in-situ dataset is conducted at three sampling stations: FH, PB and PM (see Section 3.1.3.). Model outputs are extracted at the exact times of the in-situ measurements. The comparison period spans 2001-2010, aligning with the availability of in-situ LWT dataset (see Section 3.1.3.). This evaluation is based on the following statistical metrics: coefficient of determination (R^2), normalized root-mean-squared error ($NRMSE$) and modified Willmott coefficient (d) (see Equations 1-3).

$$R^2 = \left(\frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \right)^2 \quad (1)$$

$$NRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}}{y_{max} - y_{min}} \quad (2)$$

$$d = 1 - \frac{\sum_{i=1}^{n}|y_i - x_i|}{\sum_{i=1}^{n}(|y_i - \bar{x}| + |x_i - \bar{x}|)} \quad (3)$$

where x_i and y_i are the ith observations of the COHERENS-LWT (x) and the in-situ/satellite-LWT (y), as COHERENS output is validated regarding in-situ and satellite data. $\bar{x}$ and $\bar{y}$ are their mean values. n is the number of observations.

Valid ranges for variables such as LWT, in the context of watershed simulations studies, are shown as follows. R^2, the most widely applied measure, represents the proportion of shared variance (Onyutha, 2021). It ranges from 0 to 1 and values greater than 0.5 are considered acceptable (Moriasi et al., 2007). $NRMSE$ indicates the normalized overall difference between two datasets (Chicco et al., 2021). An acceptable range is between 0 and 20% (Maniruzzaman et al., 2015a). d is the proportion of agreement between two datasets. 0 represents no agreement, and 1, perfect agreement (Willmott, 1981). An acceptable range is from 0.75. From 0.85 the performance of the model is good and more than 0.90 is very good (Moriasi et al., 2015).

3.2.2.2. Validation with satellite data

The model is also validated against Landsat-8 surface temperature imagery for the period 2013 – 2024 in accordance with data availability. Validation is performed both temporally and spatially. For temporal validation, the domain-averaged time series of surface LWT is derived for both the COHERENS output and the Landsat-8 data. The same statistical metrics used for validation against in-situ data are used here (R^2, $NRMSE$, d, Equations 1-

3). The model output is extracted to match the acquisition dates of the Landsat-8 images. Landsat 8 satellite data has been spatially interpolated on the model resolution. For spatial validation, the seasonal climatologies of surface LWT are produced for both the model and the Landsat data and the bias maps are generated. The bias is calculated as the difference between the model output and the Landsat observations. Seasonal climatologies are grouped into Austral seasons as follows: a) Summer: December-February, b) Autumn: March-May, c) Winter: June-August and d) Spring: September-November.

3.2.3. Long-term spatial and temporal patterns

An analysis of the long-term patterns of the LWT is conducted from the model simulation for the whole period (2001 - 2024). The objective here is to build the long-term anomaly of LWT to explain the interannual variability through ONI and analyze long-term trends.

A monthly spatial climatology of LWT is computed for both the surface and the bottom by extracting the 2D fields. It represents the multi-year mean of each calendar month. To derive the seasonal climatologies, monthly means were grouped into four austral seasons (DJF, MAM, JJA, SON). The surface and bottom LWT are analyzed to confirm the monomictic behaviour of the lake.

The temporal anomaly of the LWT is computed from the difference between the domain average of the LWT time series and its climatology over the period 2001 - 2024. Then we calculate the seasonal long-term trends for

LWT, for autumn, winter, spring and summer, using the Theil-Sen trend estimator and we assess their statistical significance with Mann-Kendall test. The Theil–Sen estimator is a robust method for linear regression that selects the median slope from all pairs of sample points. It is resistant to outliers and is considered the most popular nonparametric technique for estimating linear trends (Tilgenkamp, 2025). On the other hand, Mann-Kendall test chooses between the null hypothesis of trend absence against the alternative of a time series trend. If the result is 1, the null hypothesis is rejected and there is indeed a significant trend at the alpha significance level (here 0.05). On the contrary, if the result is 0, it indicates a failure to reject the null hypothesis at the alpha significance level (Fatichi, 2025).

4. Results

4.1. Model validation

4.1.1. Validation with in-situ data

Building on the configuration described in Section 3.2.2. , the results of Lake Lanalhue's LWT simulation are shown in Figure IV.2 for the period 2001-2010, focusing on one representative station (FH, see Table IV.3). The behavior across the three monitoring stations (FH, PB and PM) is similar; thus, only FH is presented for conciseness. The corresponding figures for PB and PM are provided in Appendix IV.I as supplementary material. Figure IV.2

shows that the model captures the lake's seasonal thermal structure, which is largely driven by the synoptic-scale atmospheric processes.

Both the COHERENS output and in-situ observations exhibit similar seasonal patterns. The model captures the thermal stratification during the summer (DJF) and spring (SON), and mixed conditions in autumn (MAM) and winter (JJA). While some profiles align closely with model simulated LWT (e.g. January 2002, December 2003), discrepancies exist, for instance the case of April 2008, where the in-situ data show pronounced stratification that is not fully captured by the model.

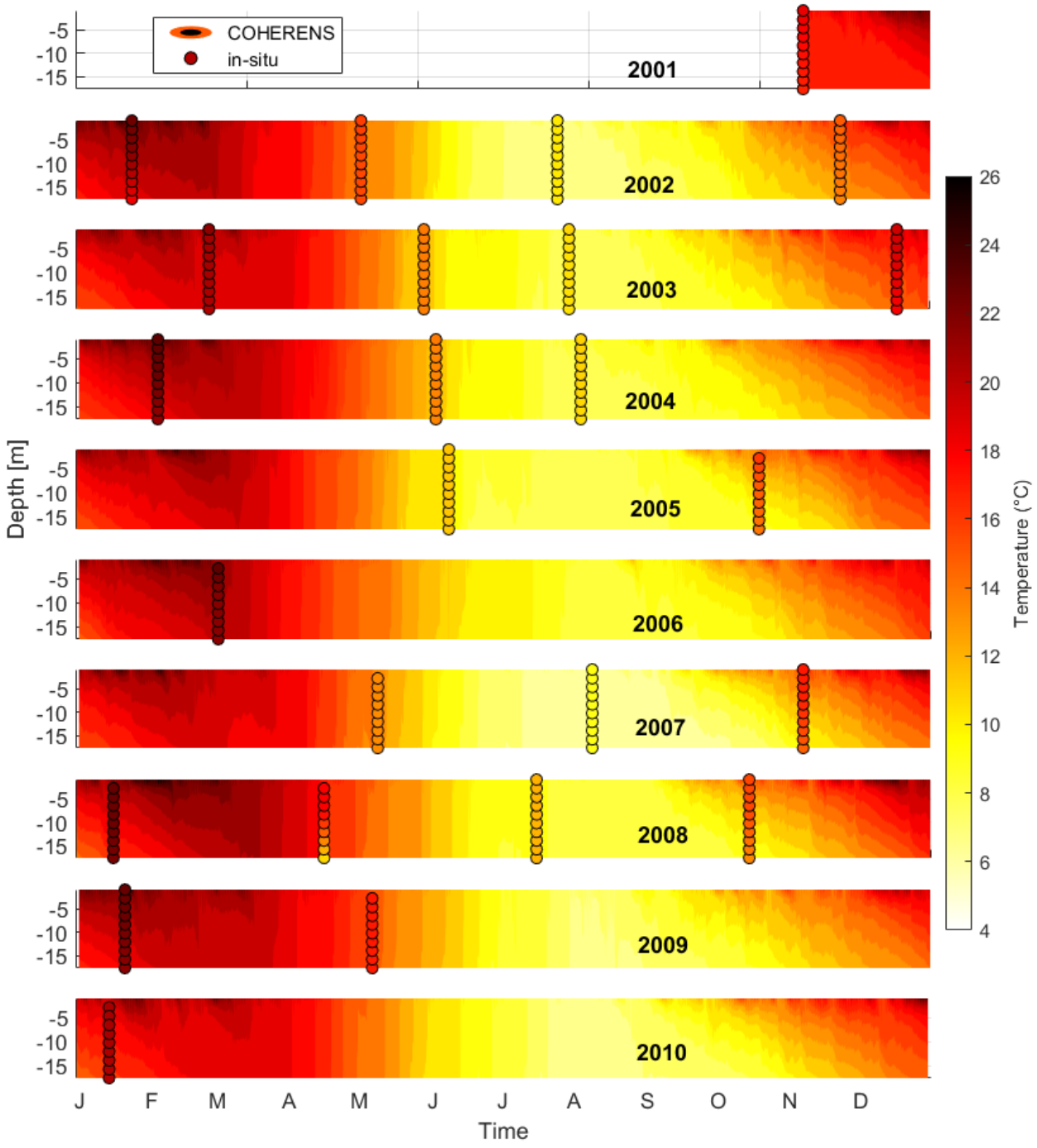


Figure IV.2. Time–depth evolution of lake water temperature (LWT) at station FH for 2001–2010. Contour shading shows COHERENS output (10 zeta-levels, archived hourly). Dots indicate in-situ temperature profiles. The in-situ measurements were taken at four nominal depths (Table 2) and vertically interpolated onto the 10 model levels for a consistent comparison. The first observed profile was used to initialize the COHERENS temperature field across the lake (Section 3.1.3).

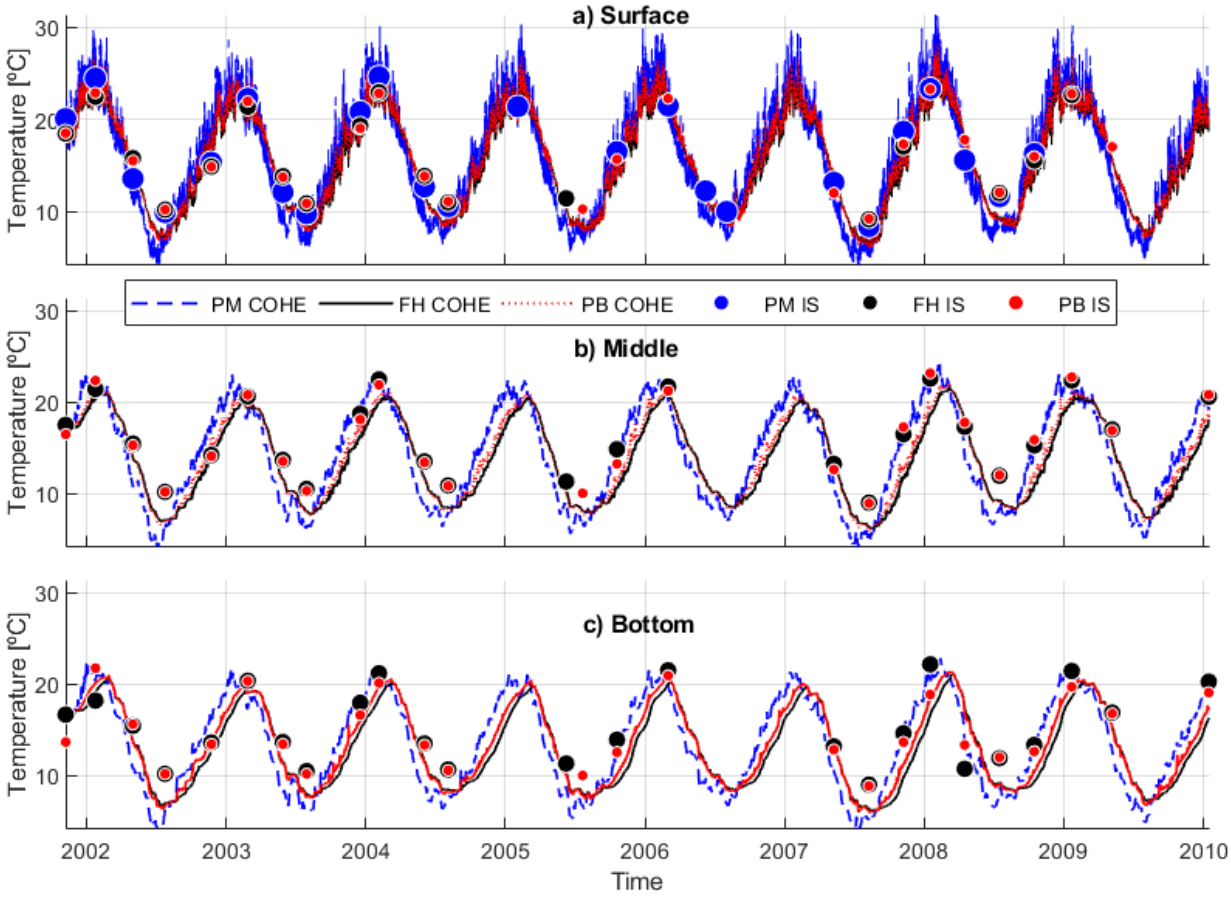


Figure IV.3. Comparison of LWT time series between in-situ (IS) and COHERENS (COHE) outputs at (a) surface, (b) middle depth and (c) bottom layers. In-situ profiles, originally collected at four depths are interpolated to ten levels to be consistent with the COHERENS vertical resolution (see Figure 2). All stations shown at the surface; middle and bottom layers exclude PM due to limited data availability.

The comparison of LWT time series between in-situ and COHERENS outputs reveals strong agreement across the stations, as it is shown in Table IV.4. The PM station, located in a shallower and sheltered southeastern area of the lake, shows the largest deviation, primarily due to faster temperature fluctuations (Figure IV.3). Across all depths, the model tracks the in-situ data

closely. The R^2 values ranging from 0.69 to 0.97, and Wilmott's index (*d) values* between 0.88 and 0.98. These metrics improve toward the surface, indicating better model performance near the surface. Similarly, *NRMSE* increases slightly from 0.12 (surface) to 0.16 (bottom), confirming this trend.

Table IV.4. Statistical comparison (R^2, NRMSE and d; see Equations 1-3) of COHERENS versus in-situ LWT for 2001-2010 at stations FH, PB and PM (see Figure 1). Data extracted and interpolated to 10 vertical levels. COHERENS outputs are extracted at in-situ LWT dates. PM results are shown only for surface, in accordance with in-situ data availability.

Station	Level	Statistics		
		R^2	$NRMSE$	d
FH	1 (Surface)	0.97	0.13	0.98
PB		0.95	0.12	0.97
PM		0.94	0.13	0.97
FH	2	0.95	0.13	0.97
PB		0.94	0.13	0.97
FH	3	0.94	0.14	0.96
PB		0.94	0.13	0.97
FH	4	0.93	0.15	0.95
PB		0.93	0.14	0.96
FH	5	0.92	0.16	0.95
PB		0.92	0.15	0.96
FH	6	0.90	0.17	0.94
PB		0.91	0.16	0.95
FH		0.86	0.18	0.93

PB	7	0.90	0.16	0.95
FH	8	0.81	0.19	0.92
PB		0.90	0.15	0.95
FH	9	0.76	0.21	0.90
PB		0.89	0.16	0.95
FH	10 (Bottom)	0.69	0.23	0.88
PB		0.87	0.16	0.94

4.1.2. Validation with satellite data

This section presents a comparison between COHERENS model output and Landsat 8 satellite-derived surface LWT, for the period 2013 - 2024. The analysis includes domain averaged surface temperature time series and seasonal climatology (Figure IV.4).

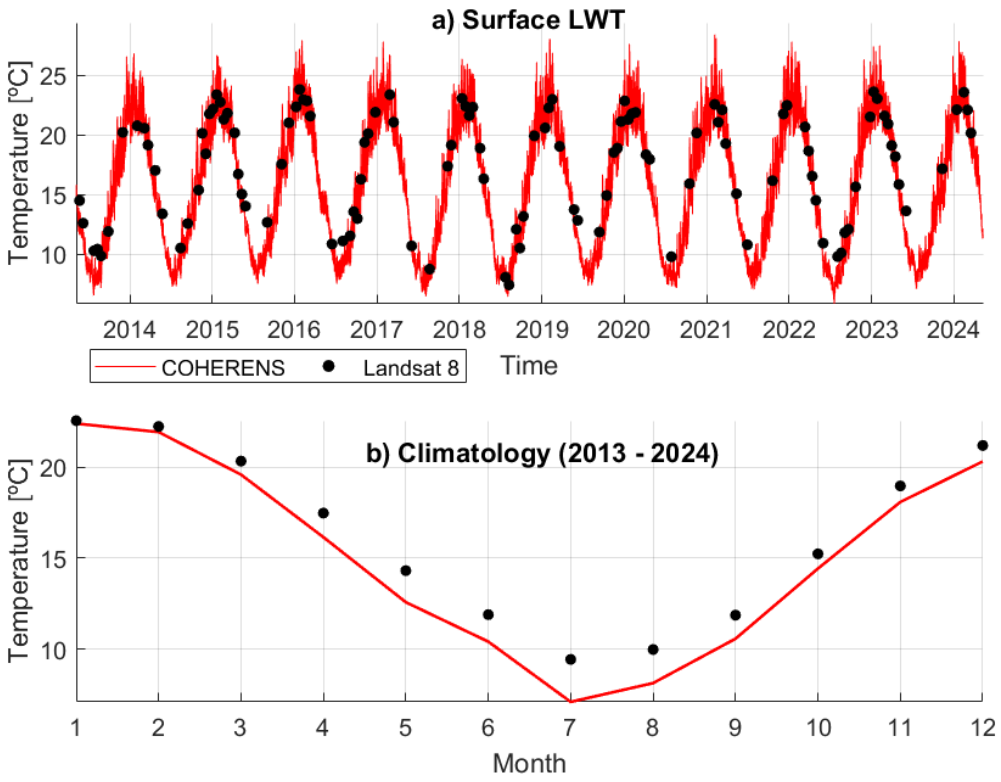


Figure IV.4. a) Domain average of superficial LWT time series for the period 2013 - 2024. Time series: COHERENS output (continuous line) and Landsat 8 observation (overlapping dots). b) Climatology of both time series.

Figure IV.4a displays the domain-averaged time series of surface LWT. There is a very good agreement between the model and Landsat 8 observation as it is evident from the statistical metrics (R^2 = 0.91, $NRMSE$ = 0.10 and d = 0.97; see Section 3.2.2.). Figure IV.4b shows the climatology of the shared dates across the same period, revealing a consistent annual cycle, ranging from 7.2°C in July (winter) to 23°C in January (summer). To assess the spatial agreement, Figure IV.5 presents the seasonal climatologies for both

COHERENS and Landsat 8 surface LWT and the bias (model-observations differences).

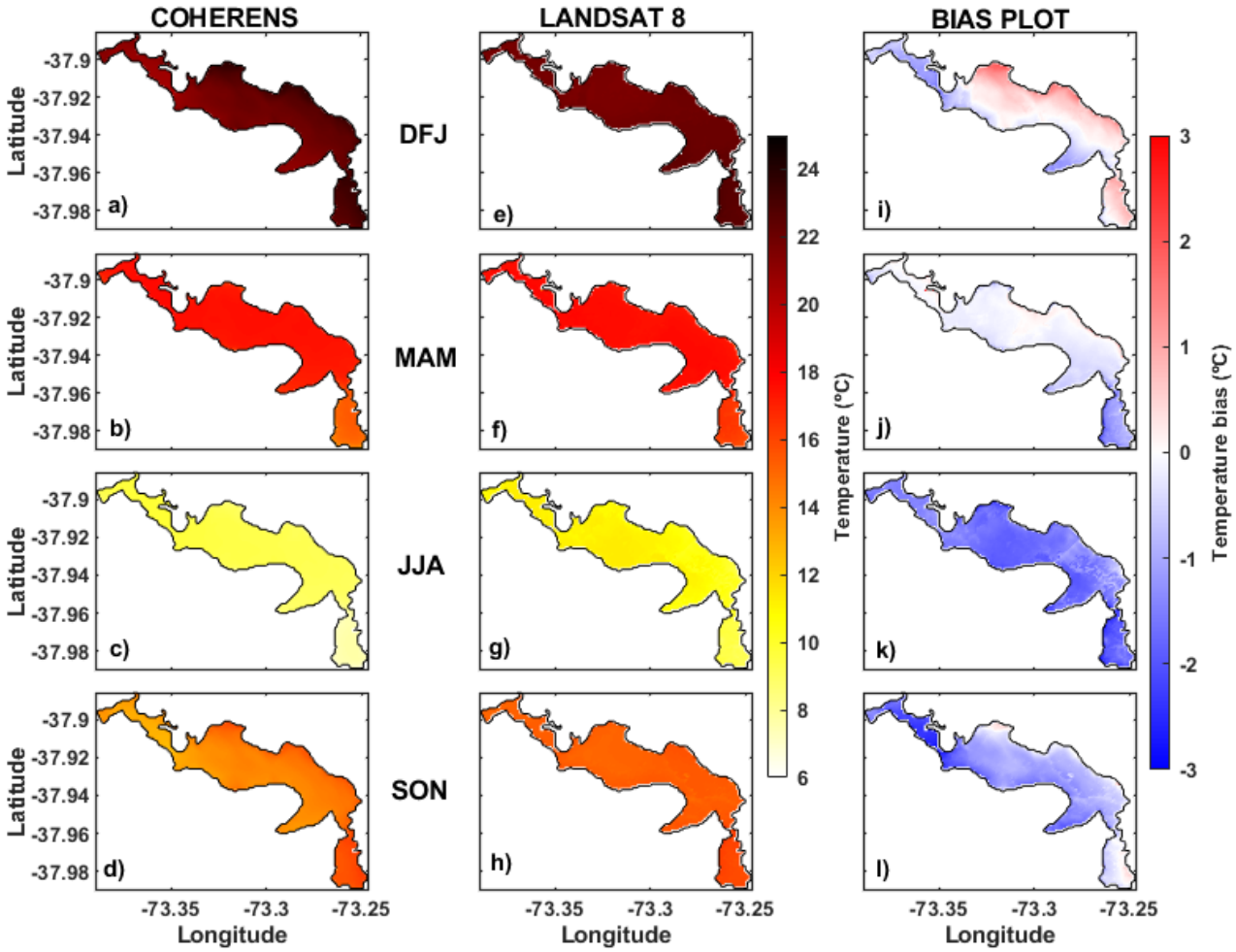


Figure IV.5. Seasonal surface LWT climatologies (2013-2024) from COHERENS model (a-d) and Landsat 8 satellite data (e-h), and corresponding bias (model minus observations, i-l). Seasons: DJF (a, e, i), MAM (b, f, j), JJA (c, g, k) and SON (d, h, l).

Overall, Figure IV.5a-h show a very good spatial pattern similarity between model simulated LWT and Landsat 8 data, including key features such as faster increase and decrease of temperature in transition seasons in

the sheltered southeast part of the lake compared to the rest of the lake (Figure IV.5b, f, d and h). Figure IV.5i-l show that most biases lie within ±1°C, with maximum differences (~2-3°C) occurring during winter (JJA, Figure IV.5c) and spring in some parts of the lake (SON, Figure IV.5d). The underestimation during winter is in agreement with the time series comparison (Figure IV.4b). This underestimation could be because of the limited availability of high quality satellite data, as shown in Section 3.1.4. .

4.2. Long-term spatial and temporal patterns

Based on the COHERENS simulation for the period 2001 - 2024, we analyze the long-term spatial and temporal patterns of lake water temperature in Lake Lanalhue. Figure IV.6 presents the seasonal climatology of LWT at both the surface and bottom.

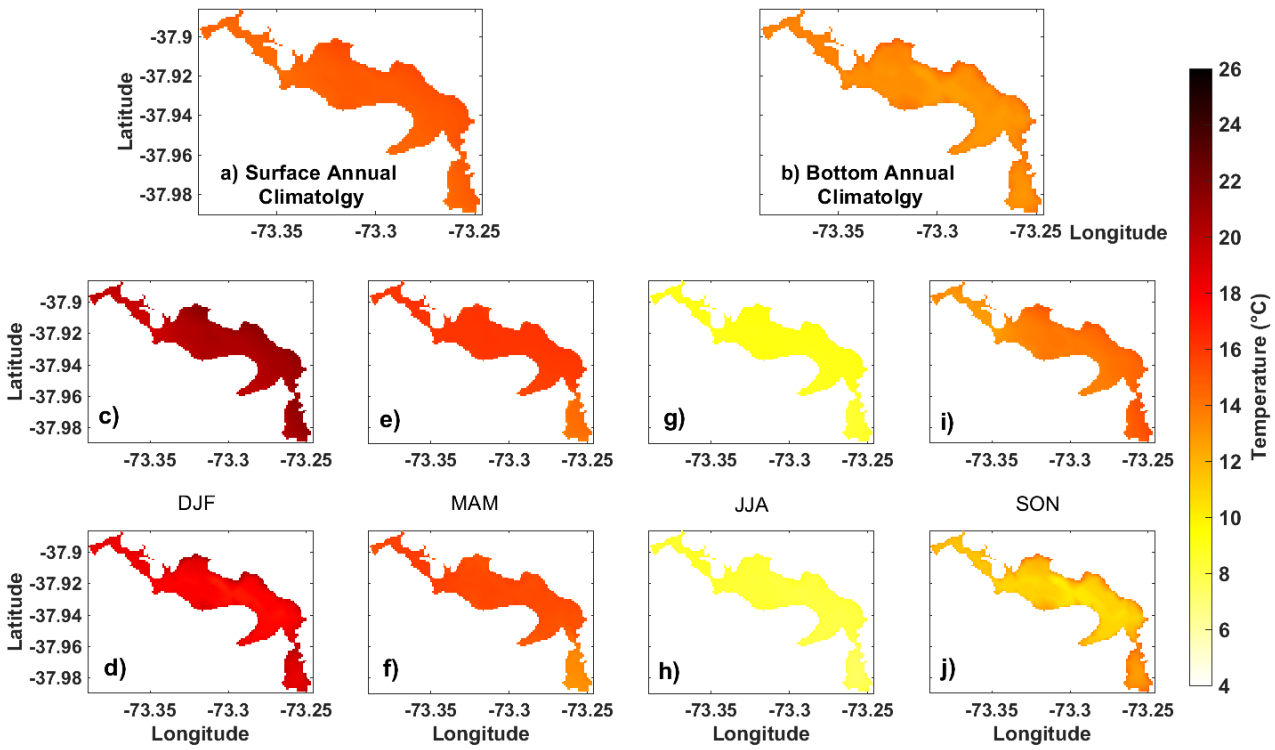


Figure IV.6. Surface and bottom LWT climatologies for the period 2001-2024. Upper panel: annual climatologies (a, b). Lower panel: seasonal climatologies, grouped by three-month periods: DJF (c,d), MAM (e,f), JJA (g,h) and SON (i,j). The colorbar is scaled to span the global minimum and maximum across all panels.

In the annual climatology (Figure IV.6a-b), there is a consistent temperature difference of approximately 2°Celsius between the surface and bottom layers. A colder area is observed in the southwestern part of the lake, in contrast to the warmer conditions in the northeast. The seasonal climatologies (Figure IV.6c—j) show stratified conditions during summer (DJF) and spring (SON), and a fully mixed water column during autumn (MAM) and winter (JJA). The southeastern part of the lake (station PM) consistently shows a more rapid temperature increase and decrease than the rest of the lake

during seasonal transitions, likely due to its shallower nature (see delay between PM and the other stations in Figure IV.3). This pattern is illustrated in a month-by-month video of the temperature climatology transition shared in (Pedreros-Guarda, 2025).

To investigate long-term temporal variability, we analyzed the surface LWT anomalies (Figure IV.7a). These anomalies were calculated as the difference between the monthly domain-averaged surface LWT and its climatological mean over the period 2001 - 2024. The Figure IV.7a is overlaid with the ONI index, highlighting the El Niño and La Niña phases and the relationship with interannual LWT variability.

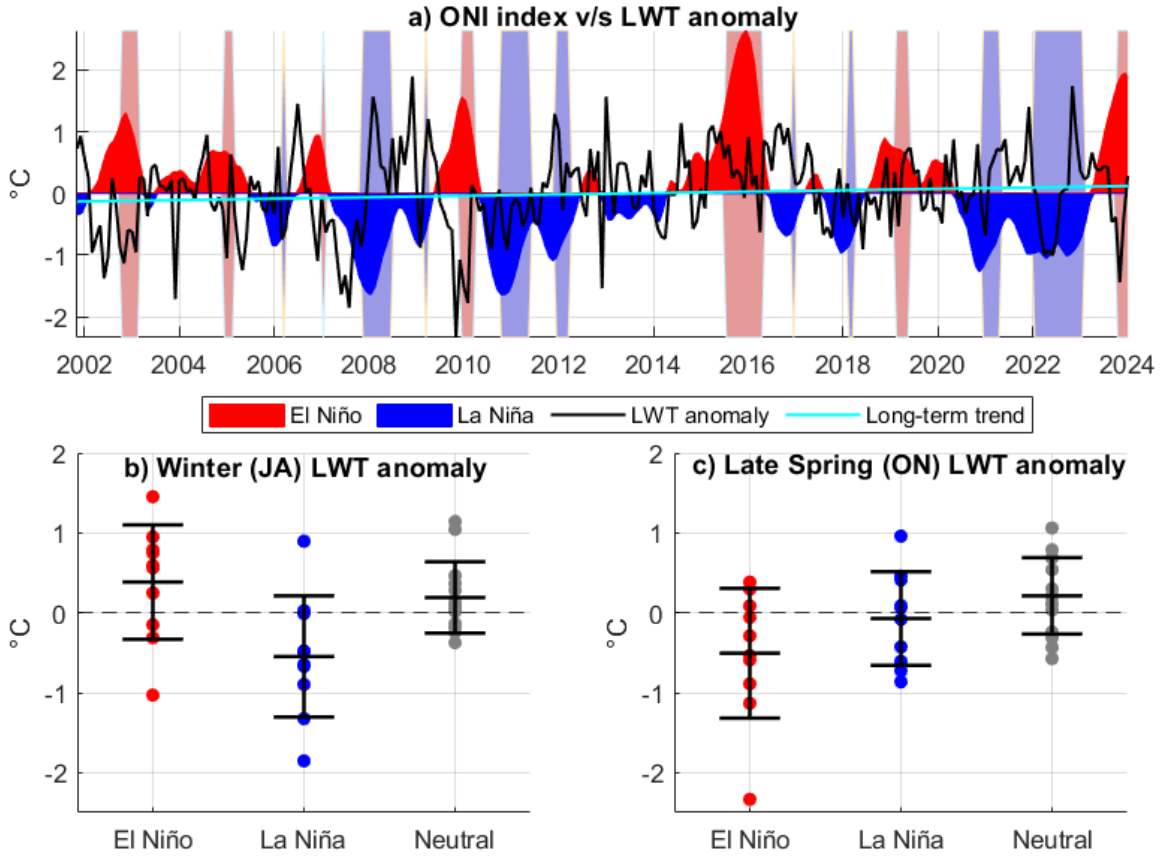


Figure IV.7. (a) Monthly anomaly of surface LWT in Lake Lanalhue for the period 2001 - 2024, computed as the domain-average minus its climatology. The ONI index is overlaid, highlighting El Niño and La Niña phases. (b) Mean LWT anomaly in July-August (JA, winter) and (c) October-November (ON, late spring. Central markers represent means, and vertical bars denote ±1 standard deviation.

The anomalies range from -2.4 to + 1.9 °C. Their interannual variability is primarily driven by the ENSO, the dominant mode of interannual climatic variability in the region (see Section 2.). Although the ENSO-LWT relationship is not immediately evident in the full time series (Figure IV.7a), it becomes clear when focusing on seasonal responses. Figure IV.7b shows surface LWT anomalies for July-August (JA; winter), and Figure IV.7c for October-November (ON; late spring). Positive anomalies of LWT are higher in El Niño years compared to La Niña years (Figure IV.7b). In El Niño years, the late springs tend to be colder than in La Niña years (Figure IV.7c), as reported by Hernandez et al. (2022).

From a long-term perspective, Theil-Sen trend estimator indicates that the lake has been under a progressive warming of 0.012 °C per year in the period 2000 – 2024. Seasonally, trends are the following: Autumn (MAM): 0.012 °C, Winter (JJA): -0.0005 °C, Spring (SON): 0.015 °C and Summer (DJF): 0.018 °C per year. The Mann-Kendall values for those trends at 0.05 confidence level are 1, indicating that there is a significant trend at a 0.05 confidence level, as explained in Section 3.2.3. .

5. Discussion

This work represents one of the few applications of 3D hydrodynamic modeling to a medium-sized lake, and among the first to adapt the coastal ocean model COHERENS to lacustrine conditions. While 3D modeling is typically reserved for large lakes due to its computational demand (Ishikawa et al., 2022), relying on 1D or 2D approaches in smaller systems often neglects essential spatial processes (Piccioni et al., 2021). Our approach fills this gap by providing a replicable methodology for medium to small-sized lakes, relying on globally available ERA5 reanalysis, a single initial vertical LWT profile, and a high resolution bathymetry interpolated from a transect campaign. This highlights the model's ability to operate under minimal data conditions, which is particularly relevant for many lakes in the Global South. In this section, we provide discussion of our work, along with critical insights into the optimal set up of lake hydrodynamical models, specifically when adapting a coastal ocean model, like COHERENS, to simulate the thermal dynamics of a lake.

COHERENS successfully reproduced the seasonal cycle of Lake Lanalhue, characterized by summer and spring stratification and full winter and autumn mixing, in agreement with in-situ and satellite observations, and consistent with the lake's monomictic regime, that mix from top to bottom during one mixing period each year. Despite the coarse spatial resolution of ERA5 (~28 km), seasonal dynamics was largely driven by large-scale

atmospheric forcing, while local may not be resolved. In this line, although model performance is remarkable (R^2 up to 0.97, NRMSE ~0.10–0.16, d > 0.88), there is scope for further improvement. Downscaling of atmospheric parameters over a region like this one brings a lot of discrepancies because of the large scale in topographic variability (Alvial Vásquez et al., 2020). There is a major limitation in obtaining meteorological forcing with higher spatial resolution while still maintaining a 1-hour temporal resolution (Alvial Vásquez et al., 2020). Future work should focus on integrating higher-resolution atmospheric data (ERA5-Land (~9 km), or setting up a high resolution atmospheric model like WRF (Alvial Vásquez et al., 2020) for the region, to incorporate local phenomena that could impact vertical stratification variability.

Beyond atmospheric resolution, it is important to clarify attribution: because the model is forced by ERA5, the simulated thermal trends primarily reflect hydroclimatic forcing (i.e., air temperature, winds, cloudiness and radiative fluxes) and how that signal is transformed by internal lake physics (mixing and stratification). There are some anthropic contributions to LSWT such as the optical properties (through attenuation coefficients) that are indirectly linked to trophic state (Pilla et al., 2018). However, most other anthropic contributions to LSWT, such as land cover/use change or the discharge of effluents at different temperatures are not included in the meteorological forcing, nor in the model parametrization.

In this study, the accuracy of the model results depended primarily on the thermal parameterization (surface heat exchange and short-wave penetration), the vertical-mixing closure, and the vertical resolution. For vertical diffusion, we tested a RANS turbulence closure and an algebraic (diagnostic) closure. Although RANS performs well in oceans and large lakes (e.g., Afsharian & Taylor, 2019; Gozingan et al., 2024), in this medium-sized system it produced excessive background mixing that prevented stratification. We therefore adopted the algebraic scheme, which preserved a realistic heating-mixing balance. Vertical resolution was also critical. A minimum of ten z-levels was required to resolve the thermocline and sustain seasonal stratification in Lake Lanalhue. We tested higher vertical resolution, but gains beyond ten layers were marginal relative to the heavy computational cost, so ten layers were retained as the practical optimum.

The model also captured the interannual variability associated with ENSO. According to (Hernandez et al., 2022), El Niño years in central-Chile are typically characterized by warmer winters and colder late springs compared to La Niña years. In our study, El Niño years (e.g., 2002, 2004, 2006, 2009, 2015) produced positive winter LWT anomalies (Figure IV.7b), reflecting enhanced atmospheric warming and reduced convective mixing, while colder-than-average conditions are seen in late springs (Figure IV.7c), likely due to delayed heat recovery or altered surface fluxes under cloudier conditions. In contrast, La Niña years (e.g., 2007, 2008, 2010, 2011, 2017) showed colder

winters and warmer late springs, with neutral years (e.g., 2001, 2003, 2005, 2012, 2013, 2014, 2016, 2018) displaying intermediate patterns. This nonlinear and seasonally modulated ENSO signature aligns with observations from other central-Chilean basins (Hernandez et al., 2022) and highlights the need to consider seasonal windows rather than annual means in climate-sensitive lake studies.

From a long-term perspective (2001–2024), Lake Lanalhue exhibited a modest warming of ~0.012 °C per year (~0.12 °C/decade), concentrated in spring (+0.015 °C/year) and summer (+0.018 °C/year), with smaller autumn warming (+0.012 °C/year) and negligible winter change, according to the Theil-Sen slope estimator. Statistically, the slopes exist at 0.05 significance level, which is given by the Mann-Kendall test. This seasonal pattern likely reflects heat accumulation during thermal stratification periods, when vertical mixing is limited, contrasted with efficient mixing and heat dissipation in winter. This warming of the lake is consistent with the progressive warming of air temperatures in the area west of the Nahuelbuta Mountain Range. While no historical air temperature record exists near Lake Lanalhue, there is a meteorological station, called Carriel Sur, located near this territorial unit west of the Nahuelbuta Mountain Range. The data from this station is listed in the (CR)2 (2025) and it shows a long-term warming trend of 0.17°C per decade (1966 - present) and 0.37°C per decade (2001-2024).

As explained in Section 2. , according to CMIP6 projections, the regional temperature will increase by 2°C, under the middle of the road scenario (SSP2-4.5) by 2080 (Salazar et al., 2024). This warming pattern will have ecological implications, such as enhanced bottom-water isolation and hypolimnetic oxygen depletion (Jansen et al., 2024; Woolway et al., 2022), or effects in the phytoplankton and algal blooms dynamics. However, in a global context, as the global average temperature increases (0.15-0.20°C per decade between 1975 and 2009), lake temperatures show an upward trend of 0.34°C per decade (global average), a trend that varies locally depending on the spatial variability of warming (O'Reilly et al., 2015). The lower warming at Lanalhue lake compared to the rest of the world is a result of the uneven warming in the planet. Before 2006, the rise of air temperatures was low or even negative in some regions of central-Chile (Falvey & Garreaud, 2009), as the southeast Pacific represents a regional cooling in a warming world. This highlights the area as a potential climate refuge in the present and future, and could therefore reinforce its status as the global conservation priority hotspot it already is (Arroyo, 2006).

Along these lines, to further explore the possibility of using the model COHERENS for lake modeling include using refined bathymetry from LiDAR or sonar surveys, and using the biogeochemical module of COHERENS to capture nutrient cycling, oxygen dynamics and bloom dynamics. Implementing these improvements would enhance both the predictive capability and the

management relevance of 3D hydrodynamic simulations in data-scarce lake environments.

This work opens the possibility to further develop a fully dedicated 3D modeling framework for lakes, so that it includes specific parametrizations appropriate for lakes. This work can provide valuable insights into the development of lake models, irrespective of the size of the lakes. to tackle important socio environmental issues related to algal blooms, contaminant dispersion, climate change, and so on.

6. Conclusion

This study a long-term, high-resolution 3D simulations of thermodynamics in a medium-sized lake in central-Chile, applying the COHERENS hydrodynamic model to Lake Lanalhue over a 24-year period (2001–2024). Despite relying on, a course resolution atmospheric forcing, and a single vertical profile for initialising the model, the model accurately reproduced the monomictic seasonal cycle, characterized by summer and spring stratification and full winter mixing. It also captured spatial thermal heterogeneity driven by lake morphology, with persistent summer warming in the northeastern basin and rapid transitional dynamics in the southeastern shallows. Interannual variability aligned with ENSO cycles, with El Niño years producing warmer winters and cooler late springs, while La Niña years exhibited the opposite pattern. Over the simulation period, the lake exhibited a

warming trend of ~0.12 °C per decade, primarily during spring and summer, achieving 0.18°C in summer, with Mann-Kendall test indicating statistical significance. The lake warming aligns with nearby in-situ air-temperature trends (~0.17 °C/dec since 1966) and unfolds within a broader context in which the southeast Pacific shows regional cooling despite global warming, highlighting the area as a potential climate refuge and reinforcing its conservation-priority status.

This work demonstrates the feasibility of adapting a 3D hydrodynamic coastal ocean model to a medium-sized, data-scarce lake. A careful selection of thermal parameterizations and vertical resolution (≥10 layers) was essential to simulate a realistic seasonal stratification. Overall, the approach outlined here bridges an important knowledge gap in Southern Hemisphere lake modeling, advancing scientific understanding and providing practical tools for climate impact assessments, adaptive monitoring, and the management of climate-sensitive freshwater ecosystems in regions vulnerable to environmental variability.

Acknowledgements: We acknowledge the support by the Royal Belgium Institute of Natural Sciences (RBINS) and its ECOMOD team in Brussels, Belgium, for hosting the first author during the development of this research. We also express our sincere thanks to Dr. Roberto Urrutia from

EULA-Chile for providing the essential bathymetric data that was crucial to this study.

Funding: The first author is thankful for the financial support from Ph.D scholarship ANID BECAS/DOCTORADO NACIONAL 21212143, and a travel grant, enabling further research and presentation opportunities related to this study. She is also thankful for the support from Universidad de Concepción, for contributing to the funding of the internship.

Credit authorship contribution statement: María Pedreros-Guarda: Conceptualization, Methodology, Software, Validation, Formal Analysis, Writing - Original Draft, Funding Acquisition. **Saheed Puthan-Purayil:** Supervision, Conceptualization, Methodology, Software, Writing - Review & Editing Resources. **Rodrigo Abarca-del-Río:** Conceptualization, Writing - Review & Editing, Funding Acquisition. **Francisco Alvial:** Data Curation. **Hugo Romanelli:** Data Curation, Resources, Software. **Olivier Gourgue:** Writing - Review & Editing, Resources. **Geneviève Lacroix:** Writing - Review & Editing, Supervision, Project administration, Resources.

Disclosure statement: No potential conflict of interest was reported by the authors.

Appendix IV.I

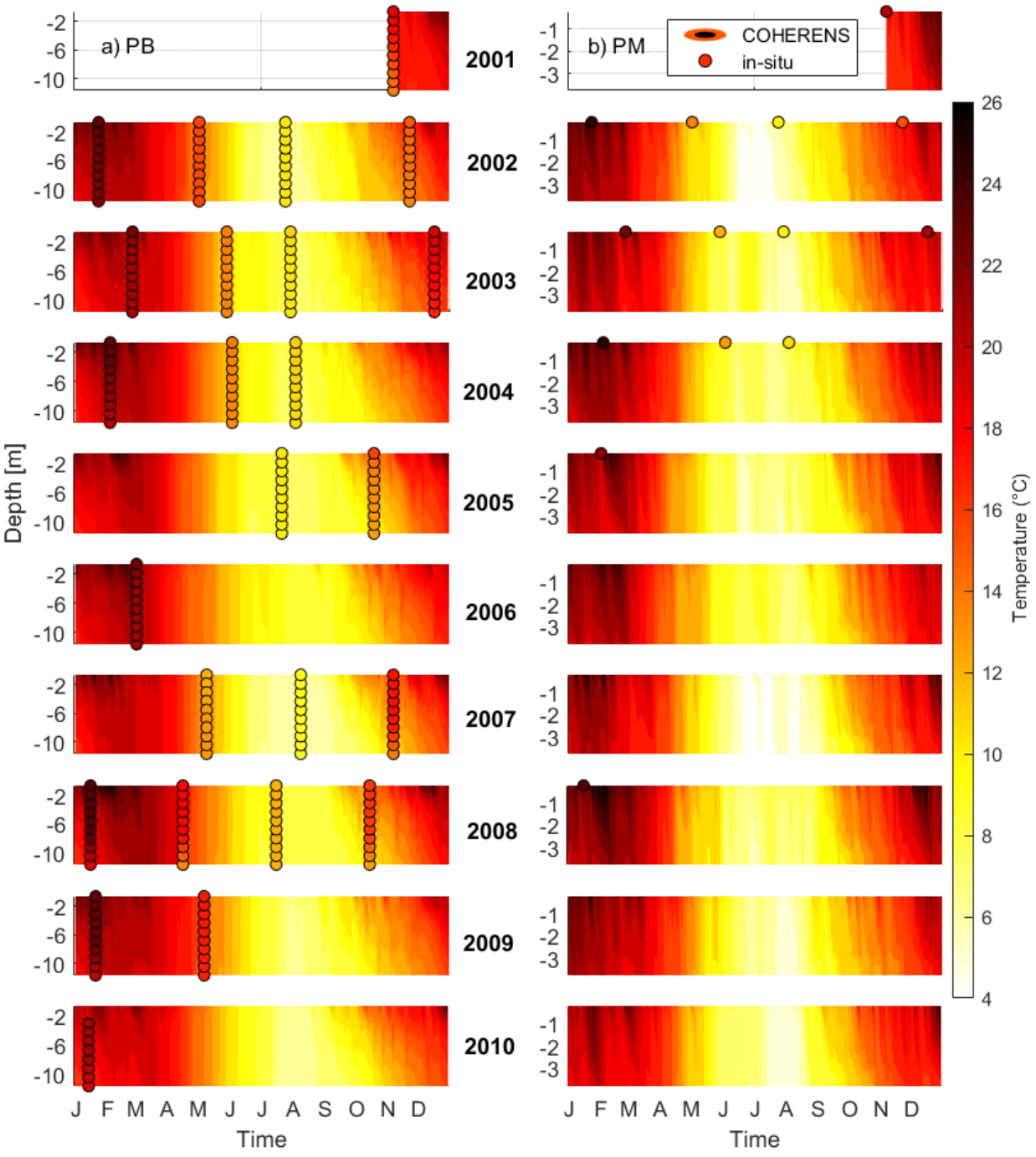


Figure A1. LWT profiles from COHERENS (contour shading) and in-situ observations (overlaid dots) at a) PB and b) PM stations for 2001-2010. COHERENS uses 10 zeta-

levels and hourly resolution, driven by ERA5 meteorological forcing. In-situ profiles, originally collected at four depths (Table IV.2), were interpolated to ten levels. Note that the first profile is used as initial conditions for COHERENS across the lake (see Section 3.1.3.).

References

Abarca-Del-Rio, R., CrÉtaux, J.-F., Berge-Nguyen, M., & Maisongrande, P. (2012). Does Lake Titicaca still control the Lake Poopó system water levels? An investigation using satellite altimetry and MODIS data (2000–2009). *Remote Sensing Letters*, *3*(8), 707-714. https://doi.org/10.1080/01431161.2012.667884

Abarzúa et al. (2020). *Informe final: Análisis de Testigo Sedimentari... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Informe%20final%3A%20An%C3%A1lisis%20de%20Testigo%20Sedimentario%20en%20Lago%20Lanalhue%2C%20Provincia%20de%20Arauco%2C%20Regi%C3%B3n%20del%20Biob%C3%ADo&author=A.M.%20Abarz%C3%BAa&publication_year=2020

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, *5*(1), 170191. https://doi.org/10.1038/sdata.2017.191

Abubakar, H. B. (2024). *Evaluation of high-resolution precipitation datasets CHIRPS, TerraClimate and TAMSAT over the Enkangala Escarpment of South Africa*. Research Square. https://doi.org/10.21203/rs.3.rs-4365508/v1

Adjovu, G. E., Stephen, H., James, D., & Ahmad, S. (2023). Overview of the Application of Remote Sensing in Effective Monitoring of Water Quality Parameters. *Remote Sensing*, *15*(7), 1938. https://doi.org/10.3390/rs15071938

Afsharian, S., & Taylor, P. A. (2019). On the Potential Impact of Lake Erie Wind Farms on Water Temperatures and Mixed-Layer Depths: Some Preliminary 1-D Modeling Using COHERENS. *Journal of Geophysical Research: Oceans*, *124*(3), 1736-1749. https://doi.org/10.1029/2018JC014577

Agência Nacional de Águas. (2010). *NORMAS DE COBRANÇA PELO USO DE RECURSOS HÍDRICOS*. https://www.ana.gov.br/arquivos/institucional/sge/CEDOC/Catalogo/2010/NormasDeCobrancaPeloUsoDosRecursosHidricos2010.pdf

Agência Nacional de Águas e Saneamento Básico (ANA). (2025). *Qualidade da água*. https://www.gov.br/ana/pt-br/assuntos/monitoramento-e-eventos-criticos/qualidade-da-agua/qualidade-da-agua

Aguayo Arias, M. I. (2008). *El cambio de uso del suelo en el centro sur de Chile. Comprendiendo su dinámica a través de la modelación espacialmente explícita y explorando sus efectos ambientales en una cuenca hidrológica de meso escala.* [[PhD Thesis], Universidad de Concepción]. https://repositorio.udec.cl/handle/11594/6004

Aguayo, M., Pauchard, A., Azócar, G., & Parra, O. (2009). Cambio del uso del suelo en el centro sur de Chile a fines del siglo XX: Entendiendo la dinámica espacial y temporal del paisaje. *Revista chilena de historia natural*, *82*(3), 361-374.

Alaniz, A. J., Abarzúa, A. M., Martel-Cea, A., Jarpa, L., Hernández, M., Aquino-López, M. A., & Smith-Ramírez, C. (2021). Linking sedimentological and spatial analysis to assess the impact of the forestry industry on soil loss: The case of Lanalhue Basin, Chile. *CATENA*, *207*, 105660. https://doi.org/10.1016/j.catena.2021.105660

Alaniz, A. J., Smith-Ramírez, C., Rendón-Funes, A., Hidalgo-Corrotea, C., Carvajal, M. A., Vergara, P. M., & Fuentes, N. (2022). Multiscale spatial analysis of headwater vulnerability in South-Central Chile reveals a high threat due to deforestation and climate change. *Science of The Total Environment*, *849*, 157930. https://www.sciencedirect.com/science/article/pii/S004896972205029X

Albus, K. H., Thompson, R., Mitchell, F., Kennedy, J., & Ponette-González, A. G. (2020). Accuracy of long-term volunteer water monitoring data: A multiscale analysis from a statewide citizen science program. *PLOS ONE*, *15*(1), e0227540. https://doi.org/10.1371/journal.pone.0227540

Alfonso, L., Gharesifard, M., & Wehn, U. (2022). Analysing the value of environmental citizen-generated data: Complementarity and cost per observation. *Journal of Environmental Management*, *303*, 114157. https://doi.org/10.1016/j.jenvman.2021.114157

Allan, M. G., Hamilton, D. P., Trolle, D., Muraoka, K., & McBride, C. (2016). Spatial heterogeneity in geothermally-influenced lakes derived from atmospherically corrected Landsat thermal imagery and three-dimensional hydrodynamic modelling. *International Journal of Applied Earth Observation and Geoinformation*, *50*, 106-116. https://doi.org/10.1016/j.jag.2016.03.006

Almanza, V., Parra, O., De M. Bicudo, C. E., Baeza, C., Beltran, J., Figueroa, R., & Urrutia, R. (2016). Occurrence of toxic blooms of Microcystis aeruginosa in a central Chilean (36° Lat. S) urban lake. *Revista Chilena de Historia Natural*, *89*(1), 8. https://doi.org/10.1186/s40693-016-0057-7

Altieri, M. A., & Rojas, A. (1999). Ecological Impacts of Chile's Neoliberal Policies, with Special Emphasis on Agroecosystems. *Environment, Development and Sustainability*, *1*(1), 55-72.

Altman, D. G. (1990). *Practical Statistics for Medical Research*. Chapman and Hall/CRC. https://doi.org/10.1201/9780429258589

Alvial Vásquez, F.-J., Abarca-del-Río, R., & Ávila, A. I. (2020). High-Resolution Precipitation Gridded Dataset on the South-Central Zone (34° S–41° S) of Chile. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.519975

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M., Moghaddam, S. H. A., Mahdavi, S., Ghahremanloo, M., Parsian, S., Wu, Q., & Brisco, B. (2020). Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 5326-5350. https://doi.org/10.1109/JSTARS.2020.3021052

Amour, I., & Kauranne, T. (2017). A variational ensemble Kalman filtering method for data assimilation using 2D and 3D version of COHERENS model. *International Journal for Numerical Methods in Fluids*, *83*(6), 544-558. https://doi.org/10.1002/fld.4276

Angrosino, M. (2012). *Etnografía y observación participante en Investigación Cualitativa*. Ediciones Morata.

Araos, F., Catalán, E., Nuñez, D., Riquelme, W., Cortinez, V., de Fina, D., & Anbleyth-Evans, J. (2023). Cuidando la Patagonia Azul: Prácticas y estrategias de los pueblos originarios para curar las zonas marinas del sur de Chile. *The Journal of Latin American and Caribbean Anthropology*, *28*(4), 286-297. https://onlinelibrary.wiley.com/doi/abs/10.1111/jlca.12695

Araya. (2019). *Desafíos del turismo y la conservación de la biodiversidad* (Primera edición, septiembre de 2019). Amukan Editorial itinerante.

Ardiantiono, Deere, N. J., Seaman, D. J. I., Mamat Rahmat, U., Ramadiyanta, E., Lubis, M. I., Trihangga, A., Yasin, A., Alza, G., Sari, D. P., Daud, M., Abdullah, R., Mutia, R., Melvern, D., Tarmizi, Supriatna, J., & Struebig, M. J. (2025). Improved cost-effectiveness of species monitoring programs through data integration. *Current Biology*, *35*(2), 391-397.e3. https://doi.org/10.1016/j.cub.2024.11.051

Argyilan, E. P., & Forman, S. L. (2003). Lake Level Response to Seasonal Climatic Variability in the Lake Michigan-Huron System from 1920 to 1995. *Journal of Great Lakes Research*, *29*(3), 488-500. https://doi.org/10.1016/S0380-1330(03)70453-5

Aróstegui, M. G. (2001). Cultura de la resistencia. Concepciones teóricas y metodológicas para su estudio. *Islas*, (127), 20-41. http://islas.uclv.edu.cu/index.php/islas/article/download/721/646

Arroyo, M. T. K. (2006). *El hotspot chileno, prioridad mundial para la conservación. Diversidad de ecosistemas, ecosistemas terrestres*.

Arsen, A., Crétaux, J.-F., Berge-Nguyen, M., & Del Rio, R. A. (2014). Remote Sensing-Derived Bathymetry of Lake Poopó. *Remote Sensing*, *6*(1), 407-420. https://doi.org/10.3390/rs6010407

Ascencio, E., Rivera, P., Cruces, F., Vila, I., Ascencio, E., Rivera, P., Cruces, F., & Vila, I. (2018). Estudio morfológico de Naiadinium polonicum (Dinophyceae) reportado por primera vez en aguas continentales de Chile. *Gayana. Botánica*, *75*(1), 438-446. https://doi.org/10.4067/S0717-66432018000100438

Assumpção, T. H., Popescu, I., Jonoski, A., & Solomatine, D. P. (2018). Citizen observations contributing to flood modelling: Opportunities and challenges. *Hydrology and Earth System Sciences*, *22*(2), 1473-1489. https://doi.org/10.5194/hess-22-1473-2018

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., Van Den Hurk, B., Hirschi, M., & Betts, A. K. (2009). A Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System. *Journal of Hydrometeorology*, *10*(3), 623-643. https://doi.org/10.1175/2008JHM1068.1

Banco Central de Chile. (2025). *Base de Datos Estadísticos (BDE)*. https://si3.bcentral.cl/siete/ES/Siete/Cuadro/CAP_CCNN/MN_CCNN76/CCNN_EP18_05_ratio

Baracchini, T., Hummel, S., Verlaan, M., Cimatoribus, A., Wüest, A., & Bouffard, D. (2020). An automated calibration framework and open source tools for 3D lake hydrodynamic models. *Environmental Modelling & Software*, *134*, 104787. https://doi.org/10.1016/j.envsoft.2020.104787

Barría, P., Chadwick, C., Ocampo-Melgar, A., Galleguillos, M., Garreaud, R., Díaz-Vasconcellos, R., Poblete, D., Rubio-Álvarez, E., & Poblete-Caballero, D.

(2021). Water management or megadrought: What caused the Chilean Aculeo Lake drying? *Regional Environmental Change*, *21*(1), 19. https://doi.org/10.1007/s10113-021-01750-w

Barros Delgado, B. B. J. (2022). *Dinámica de los asentamientos rurales y su relación con la expansión forestal en las comunas de Curanilahue, Lebu y Los Álamos, entre el periodo 1960—2002*. https://repositorio.uchile.cl/handle/2250/188639

Batina, A., & Krtalić, A. (2024). Integrating Remote Sensing Methods for Monitoring Lake Water Quality: A Comprehensive Review. *Hydrology*, *11*(7), 92. https://doi.org/10.3390/hydrology11070092

BCN. (2024). *Biblioteca del Congreso Nacional de Chile. Glosario de términos geográficos*. https://www.bcn.cl/siit/glosario/index_html

BCNa. (2024). *Reporte Comunal—Biblioteca del Congreso Nacional de Chile*. https://www.bcn.cl/siit/reportescomunales/comunas_v.html?anno=2023&idcom=8108

BCNb. (2017). *Buscador Estadístico—SIIT*. https://www.bcn.cl/siit/estadisticasterritoriales//resultados-consulta?id=326233

BCNc. (2024). *Chile: Población censada y tasas de crecimiento medio anual, según ciudades, 1950-2002*. https://www.memoriachilena.gob.cl/602/w3-article-74944.html

Beguería, S., Vicente Serrano, S. M., Reig-Gracia, F., & Latorre Garcés, B. (2023). *SPEIbase v.2.9 [Dataset]* [Dataset]. DIGITAL.CSIC. https://doi.org/10.20350/digitalCSIC/15470

Belete, M. D., Diekkrüger, B., & Roehrig, J. (2017). Linkage between Water Level Dynamics and Climate Variability: The Case of Lake Hawassa Hydrology and ENSO Phenomena. *Climate*, *5*(1), 21. https://doi.org/10.3390/cli5010021

Bengoa, J. (2000). *Historia del pueblo mapuche: (Siglo XIX y XX)*. Lom Ediciones.

Bengtsson, L. (2012). Water Balance of Lakes. En L. Bengtsson, R. W. Herschy, & R. W. Fairbridge (Eds.), *Encyclopedia of Lakes and Reservoirs* (pp. 863-864). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4410-6_18

Betts, A. K., Reid, D., & Crossett, C. (2020). Evaluation of the FLake Model in ERA5 for Lake Champlain. *Frontiers in Environmental Science*, *8*. https://doi.org/10.3389/fenvs.2020.609254

Beutel, M. W., Horne, A. J., Roth, J. C., & Barratt, N. J. (2001). Limnological effects of anthropogenic desiccation of a large, saline lake, Walker Lake, Nevada. *Hydrobiologia*, *466*(1), 91-105. https://doi.org/10.1023/A:1014569521381

Biblioteca del Congreso Nacional. (2021, octubre 13). *Biblioteca del Congreso Nacional | Ley Chile*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Biblioteca del Congreso Nacional. (2023, septiembre 6). *Ley 21600 CREA EL SERVICIO DE BIODIVERSIDAD Y ÁREAS PROTEGIDAS Y EL SISTEMA NACIONAL DE ÁREAS PROTEGIDAS*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Bio Bio (Director). (2023, febrero 13). *Dichos de Boric por regulación de industria forestal fueron catalogados como «fuera de contexto»* [Video recording]. https://www.youtube.com/watch?v=do0zHOXR5Us

Bolados, P., Espinoza, L., & Panez, A. (2024). Una aproximación decolonial a las Zonas de Sacrificio en Chile. *Vibrant: Virtual Brazilian Anthropology*, *21*, e21603. https://www.scielo.br/j/vb/a/vtQ6tPk9TWjThNfhNJTLtcv/?lang=es

Bongioannini Cerlini, P., Saraceni, M., Silvestri, L., Meniconi, S., & Brunone, B. (2022). Monitoring the Water Mass Balance Variability of Small Shallow Lakes by an ERA5-Land Reanalysis and Water Level Measurement-Based Model. An Application to the Trasimeno Lake, Italy. *Atmosphere*, *13*(6), Article 6. https://doi.org/10.3390/atmos13060949

Bonney, P. R., Hansen, B. D., & Baldwin, C. (2023). Citizen Science and Natural Resource Management: A Social Network Analysis of Two Community-Based Water Monitoring Programs. *Society & Natural Resources*, *36*(6), 600-621. https://doi.org/10.1080/08941920.2023.2183445

Boy, F., Crétaux, J.-F., Boussaroque, M., & Tison, C. (2022). Improving Sentinel-3 SAR Mode Processing Over Lake Using Numerical Simulations. *IEEE Transactions on Geoscience and Remote Sensing*, *60*, 1-18. https://doi.org/10.1109/TGRS.2021.3137034

Bravo Ferretti, C., Sandoval-Díaz, J., Astudillo Pizarro, F., Bravo Ferretti, C., Sandoval-Díaz, J., & Astudillo Pizarro, F. (2022). Narrativas del acorralamiento. Identidad de Lugar en la Bahía de Coronel a partir de la reconversión productiva. *Revista de historia (Concepción)*, *29*(1), 73-105. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-88322022000100073&lng=es&nrm=iso&tlng=en

Bravo Orrego, C. M. (2018). *Caracterización de la precipitación en la Cordillera de Nahuelbuta según la microfísica bajo la cual ocurre* [[PhD Thesis], Universidad de Chile]. https://repositorio.uchile.cl/handle/2250/168171

Brown, C. F., Brumby, S. P., Guzder-Williams, B., Birch, T., Hyde, S. B., Mazzariello, J., Czerwinski, W., Pasquarella, V. J., Haertel, R., Ilyushchenko, S., Schwehr, K., Weisse, M., Stolle, F., Hanson, C., Guinan, O., Moore, R., & Tait, A. M. (2022). Dynamic World, Near real-time global 10 m land use land cover mapping. *Scientific Data*, *9*(1), 251. https://www.nature.com/articles/s41597-022-01307-4

Budds, J. (2013). Water, Power, and the Production of Neoliberalism in Chile, 1973–2005. *Environment and Planning D: Society and Space*, *31*(2), 301-318. https://doi.org/10.1068/d9511

Burić, D., & Penjišević, I. (2023). Southern Hemisphere temperature trend in association with greenhouse gases, El Niño Southern Oscillation, and Antarctic Oscillation. *Időjárás*, *127*(1), 23-42. https://doi.org/10.28974/idojaras.2023.1.2

Burns, N. (2020). *Protocol for Monitoring Trophic Levels of New Zealand Lakes and Reservoirs*.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, *2*. https://www.frontiersin.org/articles/10.3389/feart.2014.00026

Carlson, R. E. (1977). A trophic state index for lakes. *Limnology and Oceanography*, *22*(2), 361-369. https://doi.org/10.4319/lo.1977.22.2.0361

Carmona, A., & Nahuelhual, L. (2012). Combining land transitions and trajectories in assessing forest cover change. *Applied Geography*, *32*(2), 904-915. https://www.sciencedirect.com/science/article/pii/S0143622811001755

Caro, C. S. M. (2003). *Aproximación a las estrategias de sobrevivencia de las familias de la caleta de Boca Sur Viejo en San Pedro de la Paz; experiencia y estudio de caso* [[PhD Thesis]]. Universidad de Concepción.

Carrasco Henríquez, N., & Mendoza Leal, C. (2021). Restoration as a re-commoning process. Territorial initiative and global conditions in the process of water recovery in the 'Cordillera de Nahuelbuta', Chile. *Ecosystems and People*, *17*(1), 556-573. https://doi.org/10.1080/26395916.2021.1993345

Castillo, S. F. (s. f.). *Ciudad y el derecho al buen vivir: Contribución rural a la reconstrucción de espacios fragmentados Barrio Boca Sur, Concepción, Chile.*

Chazdon, R. L., Falk, D. A., Banin, L. F., Wagner, M., J. Wilson, S., Grabowski, R. C., & Suding, K. N. (2024). The intervention continuum in restoration ecology: Rethinking the active–passive dichotomy. *Restoration Ecology*, *32*(8), e13535. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.13535

Cheng, C., Du, W., Li, J., Bao, A., Ge, W., Wang, S., Ma, D., & Pan, Y. (2023). Spatiotemporal Variations of Glacier Mass Balance in the Tomur Peak Region Based on Multi-Source Altimetry Remote Sensing Data. *Remote Sensing*, *15*(17), 4143. https://doi.org/10.3390/rs15174143

Cheng, C., Xing, Z., Ye, L., Yang, J., & Xie, Z. (2024). Characteristics and Influencing Factors of Landscape Pattern Gradient Transformation of Small-Scale Agroforestry Patches in Mountain Cities. *Sustainability*, *16*(15), 6322. https://doi.org/10.3390/su16156322

Chicco, D., Warrens, M. J., & Jurman, G. (2021). The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Computer Science*, *7*, e623. https://doi.org/10.7717/peerj-cs.623

Chile_ING_ESP.xls. (s. f.). Recuperado 25 de julio de 2025, de https://www.memoriachilena.gob.cl/archivos2/pdfs/MC0018840.PDF

Choongik, C. (2025). Unequal Distribution of Climate Change Impacts across Regions: Towards Climate Justice. *Journal of Distribution Science*, *23*(4), 103-116. https://koreascience.kr/article/JAKO202512250404430.page

Choukrani, H., Lacombe, G., Zwarteveen, M., Kuper, M., Taky, A., & Hammani, A. (2023). Sense-making and shaping of temporary wetlands: A socio-hydrological analysis of dichotomous ontologies of merjas in Morocco. *Journal of Hydrology*, 130434. https://doi.org/10.1016/j.jhydrol.2023.130434

Clark, B., & York, R. (2008). Rifts and Shifts: Getting to the Root of Environmental Crises. *Monthly Review*, *60*(6), 13. http://archive.monthlyreview.org/index.php/mr/article/view/MR-060-06-2008-10_2

Clark, N. E., Eber, L. E., Laurs, R. M., Renneer, J. A., & Saur, J. F. T. (1974). *Heat exchange between ocean and atmosphere in the eastern North Pacific for 1961-71*. https://repository.library.noaa.gov/view/noaa/11864/noaa_11864_DS1.pdf

Clark, & York. (2005). Carbon metabolism: Global capitalism, climate change, and the biospheric rift. *Theory and Society*, *34*(4), 391-428. https://doi.org/10.1007/s11186-005-1993-4

CNES. (2015). *How altimetry works [online]. Toulouse, Centre national d'études spatiales (CNES)*. https://cnes.fr/en/how-altimetry-works

Comisión Presidencial para la Paz y el Entendimiento. (2025). *Resumen ejecutivo de las recomendaciones al Estado de Chile en materia de tierras y derechos del pueblo Mapuche*. Ministerio Secretaría General de la Presidencia. https://www.comisionpazyentendimiento.gob.cl/wp-content/uploads/2025/05/Resumen-Ejecutivo-Oficial-Cierre-Comision-para-la-Paz-y-el-Entendimiento.pdf

Condom, T., Martínez, R., Pabón, J. D., Costa, F., Pineda, L., Nieto, J. J., López, F., & Villacis, M. (2020). Climatological and Hydrological Observations for the South American Andes: In situ Stations, Satellite, and Reanalysis Data Sets. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.00092

Congalton, R. G., Gu, J., Yadav, K., Thenkabail, P., & Ozdogan, M. (2014). Global Land Cover Mapping: A Review and Uncertainty Analysis. *Remote Sensing*, *6*(12), 12070-12093. https://doi.org/10.3390/rs61212070

COPERNICUS. (2025). *Land Monitoring Service: Temperature and Reflectance*. https://land.copernicus.eu/en/products/temperature-and-reflectance

Corporación Junquillar. (2024). *Protocolo de monitoreo de calidad del agua en la Laguna Junquillar*.

Corporación Junquillar. (2025). *Laguna Junquillar (@lagunajunquillar) • Fotos y videos de Instagram*. https://www.instagram.com/lagunajunquillar/

Correa, M. (2021). La Historia del Despojo; El Origen de la Propiedad Particular en el Territorio. *Santiago, Chile: Ceibo-Pehuén Ediciones*.

Cosgrove, A., & Berkelhammer, M. (2018). Downwind footprint of an urban heat island on air and lake temperatures. *Npj Climate and Atmospheric Science*, *1*(1), 46. https://doi.org/10.1038/s41612-018-0055-3

(CR)2. (2025). *Explorador climático (CR)2* (Available online) [Dataset]. https://explorador.cr2.cl/

Cretaux, J., Kouraev, A., Papa, F., Bergé-Nguyen, M., Cazenave, A., Aladin, N., & Plotnikov, I. (2005). *Water balance of the Big Aral Sea from satellite remote sensing and in situ observations*. *31*.

Crétaux, J.-F., Abarca-del-Río, R., Bergé-Nguyen, M., Arsen, A., Drolon, V., Clos, G., & Maisongrande, P. (2016). Lake Volume Monitoring from Space. *Surveys in Geophysics*, *37*(2), 269-305. https://doi.org/10.1007/s10712-016-9362-6

Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011a). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011b). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., & Birkett, C. (2006). Lake studies from satellite radar altimetry. *Comptes Rendus Geoscience, La Terre observée depuis l'espace*, *338*(14), 1098-1112. https://doi.org/10.1016/j.crte.2006.08.002

CTOH. (2024, julio 10). *Altimetric Time Series Software (AITiS) [software]*. GitLab. https://gitlab.com/ctoh/altis

Cuomo, C. J. (2011). Climate change, vulnerability, and responsibility. *Hypatia*, *26*(4), 690-714.

Da Silva, J. S., Seyler, F., Calmant, S., Rotunno Filho, O. C., Roux, E., Araújo, A. A. M., & Guyot, J. L. (2012). Water level dynamics of Amazon wetlands at the watershed scale by satellite altimetry. *International Journal of Remote Sensing*, *33*(11), 3323-3353. https://doi.org/10.1080/01431161.2010.531914

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018a). Understanding the abrupt climate change in the mid-1970s from a phase-space transform perspective. *Journal of Applied Meteorology and Climatology*, *57*(11), 2551-2560. https://journals.ametsoc.org/view/journals/apme/57/11/jamc-d-17-0345.1.xml

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018b). *Understanding the Abrupt Climate Change in the Mid-1970s from a Phase-Space Transform Perspective*. https://doi.org/10.1175/JAMC-D-17-0345.1

Davidson, N. C., Fluet-Chouinard, E., & Finlayson, C. M. (2018). Global extent and distribution of wetlands: Trends and issues. *Marine and Freshwater Research*, *69*(4), 620-627. https://www.publish.csiro.au/mf/MF17019

Delgado, F., & Rist. (2016). *Las ciencias desde la perspectiva del diálogo de saberes, la transdisciplinariedad y el diálogo intercientífico*.

Deltares. (2025). *Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments User Manual Hydro-Morphodynamics Version: 4.05.* https://www.google.com/search?q=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&oq=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBBzQxOWowajSoAgCwAgE&sourceid=chrome&ie=UTF-8

DGA. (2025a). *Red hidrométrica en línea DGA.* [Dataset]. https://dga.mop.gob.cl/servicioshidrometeorologicos/Paginas/default.aspx

DGA. (2025b). *Sistema Hidrométrico en Línea | Dirección General de Aguas*. https://dga.mop.gob.cl/sistema-hidrometrico-en-linea/

Di Chiro, G. (2015). A New Spelling Of Sustainability: Engaging Feminist-Environmental Justice Theory And Practice. *Practising Feminist Political Ecologies: Moving Beyond The «Green Economy»*, 211-236. https://doi.org/10.5040/9781350221970.ch-007

Echeverría, C., Bolados, G., Rodriguez, J., Aguayo, M., & Premoli, A. (s. f.). Ecología de Paisajes Forestales. *2014*.

ECMWF. (2020). *ECMWF Confluence Wiki: 3.3. OpenIFS: Surface Model HTESSEL [online]. Reading, European Centre for Medium-Range Weather Forecasts (ECMWF).* https://confluence.ecmwf.int/display/OIFS/3.3+OpenIFS%3A+Surface+Model+HTESSEL

ECMWF. (2025). *ERA5: Data documentation—Copernicus Knowledge Base—ECMWF Confluence Wiki*. https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation

ECMWF/C3S. (2024a). *Earth Engine Data Catalog: ERA5 Monthly Aggregates [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#bands

ECMWF/C3S. (2024b). *Earth Engine Data Catalog: ERA5-Land Monthly Aggregated [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR

ECOMOD. (2025). *COHERENS modelling system. ECOMOD – Marine Ecosystem Modelling*. https://ecomod.be/projects/COHERENS/

EEDC. (2025a). *USGS Landsat 8 Level 2, Collection 2, Tier 1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

EEDC. (2025b). *WorldClim Climatology V1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/WORLDCLIM_V1_MONTHLY?hl=es-419

EEDCa. (2025). *USGS Landsat 8 Collection 2 Tier 1 and Real-Time data Raw Scenes* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_RT?hl=es-419

EEDCb. (2025). *USGS Landsat 8 Collection 2 Tier 1 TOA Reflectanc* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_TOA?hl=es-419

EEDCc. (2025). *USGS Landsat 8 Level 2, Collection 2, Tier 1* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

Elachi, C., & Van Zyl, J. J. (2006). Introduction to the physics and techniques of remote sensing. John Wiley and Sons. *New Jersey. USA 513p*.

Elachi, C., & Zyl, J. J. van. (2021). *Introduction to the Physics and Techniques of Remote Sensing*. John Wiley & Sons.

EMOL, E. M. (2023, febrero 13). *Monsalve y debate abierto por Boric sobre industria forestal: «Sería irracional que la sociedad no diera una discusión»*. Emol. https://www.emol.com/noticias/Nacional/2023/02/13/1086588/monsalve-industria-forestal.html

EROS. (2022, noviembre 9). *USGS EROS Archive—Landsat Archives—Landsat 8-9 OLI/TIRS Collection 2 Level-2 Science Products | U.S. Geological Survey*. https://www.usgs.gov/centers/eros/science/usgs-eros-archive-landsat-archives-landsat-8-9-olitirs-collection-2-level-2

ESA. (2025a). *ATSR Reprocessing for Climate: Lake Surface Water Temperature & Ice Cover (ARC-Lake)*. https://datashare.ed.ac.uk/handle/10283/88

ESA. (2025b). *Summary of RESETlakes (REmote SEnsing of Tipping points in Lakes)*. ESA Climate Office. https://climate.esa.int/en/tipping-points-research/about-resetlakes/about-resetlakes/

European Environment Agency. (2018, julio 3). *Quality element status*. https://www.eea.europa.eu/en/analysis/maps-and-charts/quality-elements-of-water-bodies-water-assessments

Falkenmark, M., & Rockström, J. (2004). *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. Earthscan.

Falvey, M., & Garreaud, R. D. (2009). Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). *Journal of Geophysical Research: Atmospheres*, *114*(D4). https://doi.org/10.1029/2008JD010519

Fang, G. H., Yang, J., Chen, Y. N., & Zammit, C. (2015). Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, *19*(6), 2547-2559. https://doi.org/10.5194/hess-19-2547-2015

Fang, X., & An, D. (2022). Evaluation on sea surface wind speed product of Fengyun-3D satellite microwave radiation imager using ERA-5 dataset. *International Journal of Remote Sensing*, *43*(10), 3671-3691. https://doi.org/10.1080/01431161.2022.2099770

Fang, X., & Stefan, H. G. (1996). Dynamics of heat exchange between sediment and water in a lake. *Water Resources Research*, *32*(6), 1719-1727. https://doi.org/10.1029/96WR00274

FAO. (2025). *NEW! Check out the Open Foris interactive story*. OpenForis. https://www.fao.org/in-action/openforis/en

Farnaz Nojavan, F. N., Kreakie, B. J., Hollister, J. W., & Qian, S. S. (2019). Rethinking the lake trophic state index. *PeerJ*, *7*, e7936. https://doi.org/10.7717/peerj.7936

Fatichi, S. (2025, agosto 1). *Mann-Kendall Test (https://www.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test), MATLAB Central File Exchange. Recuperado 1 agosto, 2025.* https://la.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test

Fernández, I. C., Manuel-Navarrete, D., & Torres-Salinas, R. (2016). Breaking resilient patterns of inequality in Santiago de Chile: Challenges to navigate towards a more sustainable city. *Sustainability*, *8*(8), 820. https://www.mdpi.com/2071-1050/8/8/820

Fernández-Manjarrés, J. F., Roturier, S., & Bilhaut, A.-G. (2018). The emergence of the social-ecological restoration concept. *Restoration Ecology*, *26*(3), 404-410. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.12685

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302-4315. https://doi.org/10.1002/joc.5086

Fischer, R., Tamayo Cordero, F., Ojeda Luna, T., Ferrer Velasco, R., DeDecker, M., Torres, B., Giessen, L., & Günter, S. (2021). Interplay of governance elements and their effects on deforestation in tropical landscapes: Quantitative insights from Ecuador. *World Development*, *148*, 105665. https://www.sciencedirect.com/science/article/pii/S0305750X21002801

Fitchett, L. L., Sorice, M. G., Cobourn, K. M., Boyle, K. J., Klug, J. L., & Weathers, K. C. (2020). Pathways to enhanced lake integrity: A Framework to assess the effectiveness of local lake associations. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *25*(2), 258-268. https://doi.org/10.1111/lre.12308

Flavelle, A. (2003). *Mapping Our Land: Community Mapping Handbook*. Lone Pine.

Fluet-Chouinard, E., Stocker, B. D., Zhang, Z., Malhotra, A., Melton, J. R., Poulter, B., Kaplan, J. O., Goldewijk, K. K., Siebert, S., Minayeva, T., Hugelius, G., Joosten, H., Barthelmes, A., Prigent, C., Aires, F., Hoyt, A. M., Davidson, N., Finlayson, C. M., Lehner, B., … McIntyre, P. B. (2023). Extensive global wetland loss over the past three centuries. *Nature*, *614*(7947), 281-286. https://www.nature.com/articles/s41586-022-05572-6

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R., Chapin, F. S., Seto, K. C., Weber, E. U., Crona, B. I., Daily, G. C., Dasgupta, P., Gaffney, O., Gordon, L. J., Hoff, H., Levin, S. A., … Walker, B. H. (2021). Our future in the Anthropocene biosphere. *Ambio*, *50*(4), 834-869. https://doi.org/10.1007/s13280-021-01544-8

Foster, J. B. (2022). *Capitalism in the Anthropocene: Ecological Ruin or Ecological Revolution*. NYU Press.

Foster, J. B., Clark, B., & York, R. (2011). *The Ecological Rift: Capitalism's War on the Earth*. NYU Press.

Frappart, F., Blarel, F., Fayad, I., Bergé-Nguyen, M., Crétaux, J.-F., Shu, S., Schregenberger, J., & Baghdadi, N. (2021). Evaluation of the Performances of Radar and Lidar Altimetry Missions for Water Level Retrievals in Mountainous Environment: The Case of the Swiss Lakes. *Remote Sensing*, *13*(11), 2196. https://doi.org/10.3390/rs13112196

Frassl, M. A., Boehrer, B., Holtermann, P. L., Hu, W., Klingbeil, K., Peng, Z., Zhu, J., & Rinke, K. (2018). Opportunities and Limits of Using Meteorological Reanalysis Data for Simulating Seasonal to Sub-Daily Water Temperature Dynamics in a Large Shallow Lake. *Water*, *10*(5), Article 5. https://doi.org/10.3390/w10050594

Freshwater Health Index. (2025). Freshwater Health Index. https://www.freshwaterhealthindex.org

Fuentes, I., Fuster, R., Avilés, D., & Vervoort, W. (2021). Water scarcity in central Chile: The effect of climate and land cover changes on hydrologic resources. *Hydrological Sciences Journal*, *66*(6), 1028-1044. https://doi.org/10.1080/02626667.2021.1903475

Fuentes-Hernández, P., Barría-Catalán, T., & Flores-Chávez, J. (2024). Estado, ferrocarril y territorio: Las estrategias gubernamentales para la ocupación de La Araucanía a fines del siglo XIX. *Revista Austral de Ciencias Sociales*, (46), Article 46. http://revistas.uach.cl/index.php/racs/article/view/7557

Fuenzalida, H. (1982). A country of extreme climate. *Chile: Essence and Evolution*, 27-35.

Fundación Terram. (2021). *MINUTA RELATIVA A LA MORTALIDAD MASIVA DE SALMONES CAUSADAS POR FLORACIONES ALGALES NOCIVAS (FAN) EN LAS REGIONES DE LOS LAGOS Y AYSÉN*. https://www.terram.cl/descargar/recursos_naturales/salmonicultura/Minuta-Mortalidad-Masiva-de-Salmones-en-Los-Lagos-y-AyseCC81n.pdf

Fustos-Toribio, I., Manque-Roa, N., Vásquez Antipan, D., Hermosilla Sotomayor, M., & Letelier Gonzalez, V. (2022). Rainfall-induced landslide early warning system based on corrected mesoscale numerical models: An application for the southern Andes. *Natural Hazards and Earth System Sciences*, *22*(6), 2169-2183. https://doi.org/10.5194/nhess-22-2169-2022

Galarce, L. C. (2020, julio 3). Protección de los ecosistemas acuáticos ante la presión de la crisis económica que viene. *CIPER Chile*. https://www.ciperchile.cl/2020/07/03/proteccion-de-los-ecosistemas-acuaticos-ante-la-presion-de-la-crisis-economica-que-viene/

Gao, H., Birkett, C., & Lettenmaier, D. P. (2012). Global monitoring of large reservoir storage from satellite remote sensing. *Water Resources Research*, *48*(9). https://doi.org/10.1029/2012WR012063

Gao, Y., Xie, Y., & Zou, D. (2020). Hydrological regime change and its ecological responses in East Dongting Lake, China. *Ecohydrology & Hydrobiology*, *20*(1), 142-150. https://doi.org/10.1016/j.ecohyd.2019.07.003

Garreaud, R. D. (2009). The Andes climate and weather. *Advances in Geosciences*, *22*, 3-11. https://doi.org/10.5194/adgeo-22-3-2009

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., & Veloso-Aguila, D. (2020). The Central Chile Mega Drought (2010–2018): A climate dynamics perspective. *International Journal of Climatology*, *40*(1), 421-439. https://doi.org/10.1002/joc.6219

Garreaud, R. D., Vuille, M., Compagnucci, R., & Marengo, J. (2009). Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology, Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives*, *281*(3), 180-195. https://doi.org/10.1016/j.palaeo.2007.10.032

Gell, P. A., Finlayson, C. M., & Davidson, N. C. (2023). 1—An introduction to the Ramsar Convention on Wetlands. En P. A. Gell, N. C. Davidson, & C. M. Finlayson (Eds.), *Ramsar Wetlands* (pp. 1-36). Elsevier. https://doi.org/10.1016/B978-0-12-817803-4.00018-8

Gerding, V. (2010). *Suelos de humedales y trumaos húmedos del sur de Chile*. http://biblioteca.cehum.org/handle/CEHUM2018/1628

Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. *Sensors*, *16*(8), 1298. https://doi.org/10.3390/s16081298

Gozingan, A. S., Sohou, Z., Baetens, K., Bonou, F., Baloïtcha, E., Gourgue, O., Romanelli, H., Capet, A., & Lacroix, G. (2024). A 3D numerical baroclinic application of the COHERENS model in the Gulf of Guinea, West Africa. *Regional Studies in Marine Science*, *79*, 103811. https://doi.org/10.1016/j.rsma.2024.103811

Granata, F., & Di Nunno, F. (2025). Pathways for Hydrological Resilience: Strategies for Adaptation in a Changing Climate. *Earth Systems and Environment*. https://doi.org/10.1007/s41748-024-00567-x

Gubrium, J. F., Holstein, J. A., Marvasti, A. B., & McKinney, K. D. (2012). *The SAGE Handbook of Interview Research: The Complexity of the Craft*. SAGE Publications.

Gudynas, E. (2014). *Cuando los extractivismos reconPguran democracias y derechos Tensiones y contradicciones bajo el progresismo realmente gobernante*.

Gudynas, E. (2015). *Derechos de la naturaleza: Ética biocéntrica y políticas ambientales*. Editorial Abya-Yala. https://books.google.es/books?hl=es&lr=&id=FONZEAAAQBAJ&oi=fnd&pg=PA5&dq=gudynas+2015+pol%C3%ADticas+ambientales&ots=XWxfwm2CuX&sig=WCdqNCNGMdVkOrztuZc7SztKDPU

Gudynas, E. (2017). Beyond varieties of development: Disputes and alternatives. En *Rising Powers and South-South Cooperation*. Routledge.

Guo, M., Zhuang, Q., Yao, H., Golub, M., Leung, L. R., Pierson, D., & Tan, Z. (2021). Validation and Sensitivity Analysis of a 1-D Lake Model Across Global Lakes.

Journal of Geophysical Research: Atmospheres, *126*(4), e2020JD033417. https://doi.org/10.1029/2020JD033417

Guo, Y., Ren, Z., Dong, Y., Zhang, P., Wang, C., Ma, Z., & He, X. (2023). Multifunctionality can be promoted by increasing agriculture-dominated heterogeneous landscapes in an agro-forestry interlacing zone in northeast China. *Landscape and Urban Planning*, *238*, 104832. https://doi.org/10.1016/j.landurbplan.2023.104832

Hammer, D. A., & Bastian, R. K. (1989). Wetlands Ecosystems: Natural Water Purifiers? En *Constructed Wetlands for Wastewater Treatment*. CRC Press.

Hansen, G. J. A., Wehrly, K. E., Vitense, K., Walsh, J. R., & Jacobson, P. C. (2022). Quantifying the resilience of coldwater lake habitat to climate and land use change to prioritize watershed conservation. *Ecosphere*, *13*(7), e4172. https://doi.org/10.1002/ecs2.4172

Hansen, G., & Stone, D. (2016). Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, *6*(5), 532-537. https://doi.org/10.1038/nclimate2896

Hargrove, A. (2021). The global water crises: A cross-national analysis of metabolic rift theory. *Journal of Political Ecology*, *28*, 2925. https://doi.org/10.2458/jpe.2925

Haustein, K., Allen, M. R., Forster, P. M., Otto, F. E. L., Mitchell, D. M., Matthews, H. D., & Frame, D. J. (2017). A real-time Global Warming Index. *Scientific Reports*, *7*(1), 15417. https://doi.org/10.1038/s41598-017-14828-5

He, C., Malcolm, S. B., Dahlberg, K. A., & Fu, B. (2000). A conceptual framework for integrating hydrological and biological indicators into watershed management. *Landscape and Urban Planning*, *49*(1), 25-34. https://doi.org/10.1016/S0169-2046(00)00047-5

Heilmayr, R., Echeverría, C., Fuentes, R., & Lambin, E. F. (2016). A plantation-dominated forest transition in Chile. *Applied Geography*, *75*, 71-82. https://www.sciencedirect.com/science/article/pii/S0143622816302600

Hernandez, D., Mendoza, P. A., Boisier, J. P., & Ricchetti, F. (2022). Hydrologic Sensitivities and ENSO Variability Across Hydrological Regimes in Central Chile (28°–41°S). *Water Resources Research*, *58*(9), e2021WR031860. https://doi.org/10.1029/2021WR031860

Herod, A. (1993). Gender Issues in the Use of Interviewing as a Research Method∗. *The Professional Geographer*, *45*(3), 305-317. https://doi.org/10.1111/j.0033-0124.1993.00305.x

Hersbach. (2023). *ERA5 hourly data on single levels from 1940 to present*. https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview

Hipsey, M. R., Bruce, L. C., Boon, C., Busch, B., Carey, C. C., Hamilton, D. P., Hanson, P. C., Read, J. S., de Sousa, E., Weber, M., & Winslow, L. A. (2019). A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geoscientific Model Development*, *12*(1), 473-523. https://doi.org/10.5194/gmd-12-473-2019

Hodges, B. R., Imberger, J., & Laval, B. (2000). *Modeling the Hydrodynamics of Stratified Lakes*.

Holling, C. S. (1986). The resilience of terrestrial ecosystems: Local surprise and global change. *Sustainable development of the biosphere*, *14*, 292-317.

Hosseini-Sadabadi, S. A., Rousseau, A. N., Sadeghian, A., Foulon, E., & Behmel, S. (2023). A 3D numerical modeling of the links between hydrodynamics, dissolved oxygen, and water temperature of a northern rural-urban shallow lake with two distinct basins. *Environmental Monitoring and Assessment*, *195*(10), 1198. https://doi.org/10.1007/s10661-023-11744-2

Hou, M., Wei, J., Chu, H., Shi, Y., Ayantobo, O. O., Xu, J., Zhu, X., & Ren, Y. (2022). Conceptual hydrological model-guided SVR approach for monthly lake level reconstruction in the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *44*, 101271. https://doi.org/10.1016/j.ejrh.2022.101271

Hu, S., Niu, Z., & Chen, Y. (2017). Global Wetland Datasets: A Review. *Wetlands*, *37*(5), 807-817. https://doi.org/10.1007/s13157-017-0927-z

Hu, S., Niu, Z., Chen, Y., Li, L., & Zhang, H. (2017). Global wetlands: Potential distribution, wetland loss, and status. *Science of The Total Environment*, *586*, 319-327. https://www.sciencedirect.com/science/article/pii/S0048969717302425

Huang, J., Yu, H., Han, D., Zhang, G., Wei, Y., Huang, J., An, L., Liu, X., & Ren, Y. (2020). Declines in global ecological security under climate change. *Ecological Indicators*, *117*, 106651. https://www.sciencedirect.com/science/article/pii/S1470160X20305884

Huang, L., Wang, J., & Chen, X. (2022). Ecological infrastructure planning of large river basin to promote nature conservation and ecosystem functions. *Journal of Environmental Management*, *306*, 114482. https://www.sciencedirect.com/science/article/pii/S030147972200055X

Huang, L., Woolway, R. I., Timmermann, A., Lee, S.-S., Rodgers, K. B., & Yamaguchi, R. (2024). Emergence of lake conditions that exceed natural temperature variability. *Nature Geoscience*, *17*(8), 763-769. https://doi.org/10.1038/s41561-024-01491-5

Huenupil-Marihuen., M., Garces-Vargas, M., Llevilao-Colil, O., L., A.-P., & Medina-Riquelme, F. (2010). *Historia de Tirúa*.

Huttula, T., & Liukko, N. (2014). *Lake Pyykösjärvi water quality model*.

IDE. (2025). *Infraestructura de datos espaciales. Geoportal de Chile*. https://www.geoportal.cl/catalog

IDE minagri. (2025). *Planificación Catastral | IDE minagri*. https://ide.minagri.gob.cl/geoweb/2019/11/22/planificacion-catastral/

Imberger, J., & Patterson, J. C. (1989). Physical Limnology. En J. W. Hutchinson & T. Y. Wu (Eds.), *Advances in Applied Mechanics* (Vol. 27, pp. 303-475). Elsevier. https://doi.org/10.1016/S0065-2156(08)70199-6

INEa. (2017). *ArcGIS Web Application*. https://ine-chile.maps.arcgis.com/apps/webappviewer/index.html?id=d0bff7af90384faa98d6ff69faa0d6d2

INEb. (2024). *Censo de Población y Vivienda*. Default. http://www.ine.gob.cl/estadisticas/sociales/censos-de-poblacion-y-vivienda/censo-de-poblacion-y-vivienda

INFOR, I. (2014). *Exportaciones forestales chilenas 2013*. INFOR. https://doi.org/10.52904/20.500.12220/20791

Interferencia. (2023, febrero 14). *Ministro de Economía confirma postergación de debate sobre nueva regulación forestal planteada por Boric*. Interferencia. https://interferencia.cl/articulos/ministro-de-economia-confirma-postergacion-de-debate-sobre-nueva-regulacion-forestal

International Lake Environment Committee, I. L. E. C. (2007). Integrated lake basin management: An introduction. *International Lake Environment Committee Foundation. Kusatsu, Japan*, *26*.

International Lake EnvironmentCommitte, I. L. E. (2005). *Managing lakes and their basins for sustainable use: A report for lake basin managers and stakeholders*. International Lake Environment Committee Foundation. https://cir.nii.ac.jp/crid/1971430859734593319

Ishikawa, M., Gonzalez, W., Golyjeswski, O., Sales, G., Rigotti, J. A., Bleninger, T., Mannich, M., & Lorke, A. (2022). Effects of dimensionality on the performance of hydrodynamic models for stratified lakes and reservoirs. *Geoscientific Model Development*, *15*(5), 2197-2220. https://doi.org/10.5194/gmd-15-2197-2022

Iturra Urzúa, J. M. (2024). *Saqueo al humedal de Quilicura. Construcciones sobre el agua*. https://repositorio.uchile.cl/handle/2250/198083

Jacques Coper, M., & Garreaud Salazar, R. (2015). *Characterization of the 1970s climate shift in South America*. https://doi.org/10.1002/joc.4120

Jansen, J., Simpson, G. L., Weyhenmeyer, G. A., Härkönen, L. H., Paterson, A. M., del Giorgio, P. A., & Prairie, Y. T. (2024). Climate-driven deoxygenation of northern lakes. *Nature Climate Change*, *14*(8), 832-838. https://doi.org/10.1038/s41558-024-02058-3

Jerlov. (1968). *Optical Oceanography*. Elsevier.

Ji, L., Senay, G. B., & Verdin, J. P. (2015). *Evaluation of the Global Land Data Assimilation System (GLDAS) Air Temperature Data Products*. https://doi.org/10.1175/JHM-D-14-0230.1

Jian, J., Ryu, D., Costelloe, J. F., & Su, C.-H. (2017). Towards hydrological model calibration using river level measurements. *Journal of Hydrology: Regional Studies*, *10*, 95-109. https://doi.org/10.1016/j.ejrh.2016.12.085

Jiang, Q., Li, W., Fan, Z., He, X., Sun, W., Chen, S., Wen, J., Gao, J., & Wang, J. (2021). Evaluation of the ERA5 reanalysis precipitation dataset over Chinese Mainland. *Journal of Hydrology*, *595*, 125660. https://doi.org/10.1016/j.jhydrol.2020.125660

Jorgensen, S. E., & Rast, W. (2007). The use of models for synthesizing knowledge for integrated lake basin management, and facilitating implementation of the World Lake Vision. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *12*(1), 3-13. https://doi.org/10.1111/j.1440-1770.2007.00316.x

Kanazawa, M. (2023). *Research Methods for Environmental Studies: A Social Science Approach* (2.ª ed.). Routledge. https://doi.org/10.4324/9781003261117

Kay, J. J., & Schneider, E. (1995). Embracing Complexity the Challenge of the Ecosystem Approach. En L. Westra & J. Lemons (Eds.), *Perspectives on Ecological Integrity* (pp. 49-59). Springer Netherlands. https://doi.org/10.1007/978-94-011-0451-7_4

Kaya, Y. (2025). Evaluation of ICESat-2 Laser Altimetry for Inland Water Level Monitoring: A Case Study of Canadian Lakes. *Water*, *17*(7), 1098. https://doi.org/10.3390/w17071098

Kaya, Y., Balik Sanli, F., & Abdikan, S. (2025). Refinement of ICESat-2 derived inland water surface levels with the TG20 local geoid model: In the case of Türkiye

lakes. *Physics and Chemistry of the Earth, Parts A/B/C*, *139*, 103900. https://doi.org/10.1016/j.pce.2025.103900

King, A. W. (1993). Considerations of Scale and Hierarchy. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Kirby, R. R., Beaugrand, G., Kleparski, L., Goodall, S., & Lavender, S. (2021). Citizens and scientists collect comparable oceanographic data: Measurements of ocean transparency from the Secchi Disk study and science programmes. *Scientific Reports*, *11*(1), 15499. https://doi.org/10.1038/s41598-021-95029-z

KNMI. (2024). *KNMI Climate explorer*. https://climexp.knmi.nl/selectindex.cgi?id=someone@somewhere

Kondo, J. (1975). Air-sea bulk transfer coefficients in diabatic conditions. *Boundary-Layer Meteorology*, *9*(1), 91-112. https://doi.org/10.1007/BF00232256

Korkou, M., Tarigan, A. K. M., & Hanslin, H. M. (2023). The multifunctionality concept in urban green infrastructure planning: A systematic literature review. *Urban Forestry & Urban Greening*, *85*, 127975. https://doi.org/10.1016/j.ufug.2023.127975

Kornijów, R. (2023). Lake aging concept revisited: Alternative comprehensive approach to lake ontogeny. *Canadian Journal of Fisheries and Aquatic Sciences*, *80*(8), 1385-1393. https://doi.org/10.1139/cjfas-2023-0027

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259-263. https://doi.org/10.1127/0941-2948/2006/0130

Kreakie, B. J., Shivers, S. D., Hollister, J. W., & Milstead, W. B. (2021). Predictive Model of Lake Photic Zone Temperature Across the Conterminous United States. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.707874

Kumar, L., & Mutanga, O. (2018). Google Earth Engine Applications Since Inception: Usage, Trends, and Potential. *Remote Sensing*, *10*(10), Article 10. https://doi.org/10.3390/rs10101509

Kwak, T. J., & Freeman, M. (2010). *Assessment and management of ecological integrity: Chapter 12*. 353-394. https://pubs.usgs.gov/publication/70154946

Labraña-Muñoz, C., & Arcas-Morales, G. (2006). San Pedro de la Paz: Del Fuerte a la comuna (1604-2001). *Hualpén, Chile: Impresos Andalién, Ilustre Municipalidad de San Pedro de la Paz*.

Lara, A., Jones, J., Little, C., & Vergara, N. (2021). Streamflow response to native forest restoration in former Eucalyptus plantations in south central Chile. *Hydrological Processes*, *35*(8), e14270. https://doi.org/10.1002/hyp.14270

Lara, A., Solari, M. E., Prieto, M. D. R., & Peña, M. P. (2012). Reconstrucción de la cobertura de la vegetación y uso del suelo hacia 1550 y sus cambios a 2007 en la ecorregión de los bosques valdivianos lluviosos de Chile (35º—43º 30´ S). *Bosque (Valdivia)*, *33*(1), 13-23. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-92002012000100002&lng=es&nrm=iso&tlng=en

Lee, J.-W., Park, S.-R., & Lee, S.-W. (2023). Effect of Land Use on Stream Water Quality and Biological Conditions in Multi-Scale Watersheds. *Water*, *15*(24), 4210. https://doi.org/10.3390/w15244210

Lee, K., Nam, S., Cho, Y.-K., Jeong, K.-Y., & Byun, D.-S. (2022). Determination of Long-Term (1993–2019) Sea Level Rise Trends Around the Korean Peninsula

Using Ocean Tide-Corrected, Multi-Mission Satellite Altimetry Data. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.810549

Lewis, S. L., & Maslin, M. A. (2015). Defining the Anthropocene. *Nature*, *519*(7542), 171-180. https://www.nature.com/articles/nature14258

Lieberherr, G., & Wunderle, S. (2018). Lake Surface Water Temperature Derived from 35 Years of AVHRR Sensor Data for European Lakes. *Remote Sensing*, *10*(7), Article 7. https://doi.org/10.3390/rs10070990

Lin, S., Boegman, L., Shan, S., & Mulligan, R. (2022). An automatic lake-model application using near-real-time data forcing: Development of an operational forecast workflow (COASTLINES) for Lake Erie. *Geoscientific Model Development*, *15*(3), 1331-1353. https://doi.org/10.5194/gmd-15-1331-2022

Little, C., Lara, A., McPhee, J., & Urrutia, R. (2009). Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile. *Journal of Hydrology*, *374*(1), 162-170. https://doi.org/10.1016/j.jhydrol.2009.06.011

Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., Valenzuela, R. A., Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., & Valenzuela, R. A. (2017). La agricultura y la élite agraria chilena a través de los catastros agrícolas, c. 1830-1855. *Historia (Santiago)*, *50*(2), 597-639. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-71942017000200597&lng=es&nrm=iso&tlng=es

Long, L. (2017, marzo 1). The Stages of Lake and Pond Succession. *SOLitude Lake Management: Full-Service Lake And Pond Management*. https://www.solitudelakemanagement.com/the-stages-of-lake-and-pond-succession/

Lovell, S. T. (2010). Multifunctional Urban Agriculture for Sustainable Land Use Planning in the United States. *Sustainability*, *2*(8), 2499-2522. https://doi.org/10.3390/su2082499

Luo, J., Duan, H., Xu, Y., Shen, M., Zhang, Y., Xiao, Q., Ni, G., Wang, K., Xin, Y., Qi, T., Feng, L., Qiu, Y., Jeppesen, E., & Woolway, R. I. (2025). Global trends and regime state shifts of lacustrine aquatic vegetation. *The Innovation*, *6*(3), 100784. https://doi.org/10.1016/j.xinn.2024.100784

Luyten, P. (2025). *COHERENS: A Coupled Hydrodynamical Ecological Model for Regional and Shelf Seas: User Documentation (Version 3)*. Operational Directorate Natural Environment, Royal Belgian Institute of Natural Sciences. https://doi.org/10.5281/zenodo.11261106.

Lyche Solheim, A., Globevnik, L., Austnes, K., Kristensen, P., Moe, S. J., Persson, J., Phillips, G., Poikane, S., van de Bund, W., & Birk, S. (2019). A new broad typology for rivers and lakes in Europe: Development and application for large-scale environmental assessments. *Science of The Total Environment*, *697*, 134043. https://doi.org/10.1016/j.scitotenv.2019.134043

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J. B., Jena, J., Bhattacharya, U., Duvvada, S. K., Lalichetti, S., & Sairam, M. (2021). Intercropping—A Low Input Agricultural Strategy for Food and Environmental Security. *Agronomy*, *11*(2), Article 2. https://www.mdpi.com/2073-4395/11/2/343

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015a). Validation of the AquaCrop model for irrigated rice production under

varied water regimes in Bangladesh. *Agricultural Water Management*, *159*, 331-340. https://doi.org/10.1016/j.agwat.2015.06.022

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015b). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*(C), 331-340. https://ideas.repec.org//a/eee/agiwat/v159y2015icp331-340.html

Mano, A., Malve, O., Koponen, S., Kallio, K., Taskinen, A., Ropponen, J., Juntunen, J., & Liukko, N. (2015). Assimilation of satellite data to 3D hydrodynamic model of Lake Säkylän Pyhäjärvi. *Water Science and Technology*, *71*(7), 1033-1039. https://doi.org/10.2166/wst.2015.042

Mano, A., & Shuku, T. (2014). *Application of the Particle Filter to COHERENS V2 model of Lake Säkylän Pyhäjärvi*.

Manuschevich, D. (2016). Neoliberalization of forestry discourses in Chile. *Forest Policy and Economics*, *69*, 21-30. https://doi.org/10.1016/j.forpol.2016.03.006

Marinov, D., Norro, A., & Zaldívar, J.-M. (2006). Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore). *Ecological Modelling, Special Issue on Southern European Coastal Lagoons*, *193*(1), 52-68. https://doi.org/10.1016/j.ecolmodel.2005.07.042

Martínez Retureta, R. (2021). *Efectos del cambio de uso cobertura del suelo sobre la respuesta hidrológica en cuencas del centro sur de Chile bajo escenarios de cambio climático.* https://repositorio.udec.cl/handle/11594/6538

Martínez-Fernández, J., Banos-González, I., & Esteve-Selma, M. Á. (2021). An integral approach to address socio-ecological systems sustainability and their uncertainties. *Science of The Total Environment*, *762*, 144457. https://www.sciencedirect.com/science/article/pii/S0048969720379882

Martínez-Tilleria, K., Núñez-Ávila, M., León, C. A., Pliscoff, P., Squeo, F. A., & Armesto, J. J. (2017). A framework for the classification Chilean terrestrial ecosystems as a tool for achieving global conservation targets. *Biodiversity and Conservation*, *26*(12), 2857-2876. https://doi.org/10.1007/s10531-017-1393-x

Marttunen, M., Hellsten, S., Glover, B., Tarvainen, A., Klintwall, L., Olsson, H., & Pedersen, T. S. (2006). Heavily regulated lakes and the European Water framework directive—Comparisons from Finland, Norway, Sweden, Scotland and Austria. *E-Water*, *5*, 1-22. https://www.ewa-online.eu/files/downloads/publications/E-Water_Journal/42_2006_05.pdf

Mason, I. M., Guzkowska, M. A. J., Rapley, C. G., & Street-Perrott, F. A. (1994). The response of lake levels and areas to climatic change. *Climatic Change*, *27*(2), 161-197. https://doi.org/10.1007/BF01093590

Mayer, A. L., & Rietkerk, M. (2004). The Dynamic Regime Concept for Ecosystem Management and Restoration. *BioScience*, *54*(11), 1013-1020. https://doi.org/10.1641/0006-3568(2004)054[1013:TDRCFE]2.0.CO;2

McDougall, T. J., Jackett, D. R., Wright, D. G., & Feistel, R. (2003). *Accurate and Computationally Efficient Algorithms for Potential Temperature and Density of Seawater*. https://journals.ametsoc.org/view/journals/atot/20/5/1520-0426_2003_20_730_aaceaf_2_0_co_2.xml

McGregor, G. (2017). Hydroclimatology, modes of climatic variability and stream flow, lake and groundwater level variability: A progress report. *Progress in Physical*

Geography: Earth and Environment, *41*(4), 496-512. https://doi.org/10.1177/0309133317726537

Meerhoff, M., Audet, J., Davidson, T. A., De Meester, L., Hilt, S., Kosten, S., Liu, Z., Mazzeo, N., Paerl, H., Scheffer, M., & Jeppesen, E. (2022). Feedback between climate change and eutrophication: Revisiting the allied attack concept and how to strike back. *Inland Waters*, *12*(2), 187-204. https://doi.org/10.1080/20442041.2022.2029317

Mellor, G. L. (1988). *A THREE-DIMENSIONAL, PRIMITIVE EQUATION, NUMERICAL OCEAN MODEL*.

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016a). Trophic State Index estimation from remote sensing of lake Chapala, México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016b). Trophic State Index estimation from remote sensing of lake Chapala, México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Meng, B., Liu, J., Bao, K., & Sun, B. (2020). Methodologies and Management Framework for Restoration of Wetland Hydrologic Connectivity: A Synthesis. *Integrated Environmental Assessment and Management*, *16*(4), 438-451. https://doi.org/10.1002/ieam.4256

Merryfield, W. J., & Lee, W.-S. (2023). Estimating Probabilities of Extreme ENSO Events from Copernicus Seasonal Hindcasts. *Asia-Pacific Journal of Atmospheric Sciences*, *59*(4), 479-493. https://doi.org/10.1007/s13143-023-00328-2

Metcalfe, A. N., Kennedy, T. A., Mendez, G. A., & Muehlbauer, J. D. (2022). Applied citizen science in freshwater research. *WIREs Water*, *9*(2), e1578. https://doi.org/10.1002/wat2.1578

Mironov, D., Golosov, S., Heise, E., Kourzeneva, E., Ritter, B., Schneider, N., & Terzhevik, A. (2005). FLake – A Lake Model for Environmental Applications. *2005*.

Mitra, S., Wassmann, R., & Vlek, P. L. G. (2003). *Global inventory of wetlands and their role in the carbon cycle* (ZEF - Discussion Papers on Development Policy No. 64). https://doi.org/10.22004/ag.econ.18771

MMA. (2020). *ANTEPROYECTO DEL PLAN DE DESCONTAMINACION POR CLOROFILA "A", TliANSPARENCIA Y FOSFORO DISUELTO, PARA LA CUENCA DEL LAGO VILLARRICA.* https://consultaindigena.mma.gob.cl/wp-content/uploads/2021/11/Anteproyecto-PDA-Lago-Villarrica.pdf

Montecinos, A., & Aceituno, P. (2003). *Seasonality of the ENSO-Related Rainfall Variability in Central Chile and Associated Circulation Anomalies*. https://journals.ametsoc.org/view/journals/clim/16/2/1520-0442_2003_016_0281_soterr_2.0.co_2.xml

Morales-Magaña, M., Paneque-Galvez, J., Torres-Abreu, A., Mori-González, R., Reyes Díaz, A. M., Rivera Ramos, J. C., Molina Carrasquillo, R., & Molina Parrilla, S. C. (2020). *Community experiences in water management: Social innovation, participatory science, and dialogue of knowledges II (in Portuguese and Spanish)*. https://doi.org/10.5281/zenodo.4362629

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, *50*(3), 885-900. https://doi.org/10.13031/2013.23153

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). *Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria*.

Mortimer, C. H. (1974). Lake hydrodynamics. *Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Mitteilungen*. (world). https://www.tandfonline.com/doi/abs/10.1080/05384680.1974.11923886

Mukaka, M. M. (2012). A guide to appropriate use of Correlation coefficient in medical research. *Malawi Medical Journal*, *24*(3), 69-71. https://www.ajol.info/index.php/mmj/article/view/81576

Muñoz Aguayo, P. (2013). *Apuntes de teledetección: Índices de vegetación.* https://bibliotecadigital.ciren.cl/bitstreams/af8fd625-0d58-4941-8530-7186a6b3d93e/download

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349-4383. https://doi.org/10.5194/essd-13-4349-2021

Naciones Unidas, M. J. (2025). Objetivos y metas de desarrollo sostenible. *Desarrollo Sostenible*. https://www.un.org/sustainabledevelopment/es/objetivos-de-desarrollo-sostenible/

NASA. (2025). *ASF Data Search*. https://search.asf.alaska.edu/

NASA SWOT. (2024). *NASA SWOT. Jet Propulsion Laboratory: Surface Water and Ocean Topography (SWOT).* https://swot.jpl.nasa.gov/

National Institute of Water and Atmospheric Research. (2025). *Lakespi (Lake Submerged Plant Indicators)*. https://lakespi.niwa.co.nz/

Ndehedehe, C. E., Awange, J. L., Kuhn, M., Agutu, N. O., & Fukuda, Y. (2017). Analysis of hydrological variability over the Volta river basin using in-situ data and satellite observations. *Journal of Hydrology: Regional Studies*, *12*, 88-110. https://doi.org/10.1016/j.ejrh.2017.04.005

Nekouee, N., Hamidi, S. A., Roberts, P. J. W., & Schwab, D. J. (2015). Assessment of a 3D Hydrostatic Model (POM) in the Near Field of a Buoyant River Plume in Lake Michigan. *Water, Air, & Soil Pollution*, *226*(7), 210. https://doi.org/10.1007/s11270-015-2488-1

Ngamile, S., Madonsela, S., & Kganyago, M. (2025). Trends in remote sensing of water quality parameters in inland water bodies: A systematic review. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1549301

Nhamo, L., Magidi, J., & Dickens, C. (2017). Determining wetland spatial extent and seasonal variations of the inundated area using multispectral remote sensing. *Water SA*, *43*(4), 543-552. https://doi.org/10.4314/wsa.v43i4.02

Nielsen, L. (2020, enero). *(PDF) Toward a unified theory of risk, resilience and sustainability science with applications for education and governance*. https://www.researchgate.net/publication/348407042_Toward_a_unified_theory_of_risk_resilience_and_sustainability_science_with_applications_for_education_and_governance

NOAA. (2024a). *El Niño / Southern Oscillation (ENSO) | Equatorial Pacific Sea Surface Temperatures (SST) | National Centers for Environmental Information (NCEI)*. https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024b). *National Oceanic and Atmospheric Administration (NOAA). Antartic Oscillation.* https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml

NOAA. (2024c). *National Oceanic and Atmospheric Administration (NOAA). Equatorial Pacific Sea Surface Temperatures (SST).* https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024d). *National Oceanic and Atmospheric Administration (NOAA). Pacific Decadal Oscillation (PDO).* https://www.ncei.noaa.gov/access/monitoring/pdo/

Odeku, K. O. (2022). Climate injustices due to the unequal and disproportionate impacts of climate change. *Perspectives of Law and Public Administration*, *11*(1), 103-110. https://www.ceeol.com/search/article-detail?id=1102605

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., & Calvez, R. (2018). Surface water monitoring in small water bodies: Potential and limits of multi-sensor Landsat time series. *Hydrology and Earth System Sciences*, *22*(8), 4349-4380. https://doi.org/10.5194/hess-22-4349-2018

Olvera, M. J. T. (2018). *Integridad ecológica como una herramienta de evaluación en cuencas hidrográficas. Caso de estudio Microcuenca del Río Jalpan*. https://ring.uaq.mx/handle/123456789/1004

Onyutha, C. (2021). A hydrological model skill score and revised R-squared. *Hydrology Research*, *53*(1), 51-64. https://doi.org/10.2166/nh.2021.071

Oppliger, A. (2015). *Atlas del Agua – Chile 2016 / Atlas of Water—Chile 2016*. Ministry of Public Works - General Direction of Waters of Chile. https://iris.unil.ch/handle/iris/49995

O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J. D., McIntyre, P. B., Kraemer, B. M., Weyhenmeyer, G. A., Straile, D., Dong, B., Adrian, R., Allan, M. G., Anneville, O., Arvola, L., Austin, J., Bailey, J. L., … Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, *42*(24), 10,773-10,781. https://doi.org/10.1002/2015GL066235

Organización del Tratado de Cooperación Amazónica. (2025). *Proyecto Cuenca Amazónica. Implementación del Programa de Acciones Estratégicas en la Cuenca del río Amazonas considerando la Variabilidad y el Cambio Climático.* https://aguasamazonicas.otca.org/monitoreo-ambiental-y-de-los-recursos-hidricos/sistema-integrado-de-monitoreo-de-los-recursos-hidricos/

Ortiz, A. M. D., Gayó, E. M., Henríquez, N. C., Henríquez, B. J., & Pauchard, A. (2024). Exploring the multifunctional landscapes model in areas dominated by non-native tree plantations. *Trees, Forests and People*, *17*, 100617. https://www.sciencedirect.com/science/article/pii/S2666719324001249

Otavo, S., & Echeverría, C. (2017). Fragmentación progresiva y pérdida de hábitat de bosques naturales en uno de los hotspot mundiales de biodiversidad. *Revista Mexicana de Biodiversidad*, *88*(4), 924-935. https://doi.org/10.1016/j.rmb.2017.10.041

Otero Durán, L. (2012). La huella del fuego: Historia de los bosques nativos poblamiento y cambios en el paisaje de lsur de Chile. *2012*. https://www.sidalc.net/search/Record/KOHA-OAI-FCF:15776/Description

Oxley, R. L. (2015). *Ecological, environmental and hydrological integrity in sustainable water resource management for river basins*. Arizona State University. https://search.proquest.com/openview/4d57cce5b508c9900cd2f564fdc817bd/1?pq-origsite=gscholar&cbl=18750

Palomo, I., Locatelli, B., Otero, I., Colloff, M., Crouzat, E., Cuni-Sanchez, A., Gómez-Baggethun, E., González-García, A., Grêt-Regamey, A., Jiménez-Aceituno, A., Martín-López, B., Pascual, U., Zafra-Calvo, N., Bruley, E., Fischborn, M., Metz, R., & Lavorel, S. (2021). Assessing nature-based solutions for transformative change. *One Earth*, *4*(5), 730-741. https://doi.org/10.1016/j.oneear.2021.04.013

Paredes, M. L., & Ulloa, M. E. (2021). Implementación de los ECMPO y las disputas por el control del territorio: El caso del ECMPO Mañihueico-Huinay y los mitilicultores de la comuna de Hualaihué, Región de Los Lagos. *Revista LIDER*, 62-87. https://revistas.ulagos.cl/index.php/index

Pareeth, S., Salmaso, N., Adrian, R., & Neteler, M. (2016). Homogenised daily lake surface water temperature data generated from multiple satellite sensors: A long-term case study of a large sub-Alpine lake. *Scientific Reports*, *6*(1), 31251. https://doi.org/10.1038/srep31251

Parra et al. (2016). *Una aproximación interdisciplinaria al estudio... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Una+aproximaci%C3%B3n+interdisciplinaria+al+estudio+de+floraciones+de+algas+nocivas+en+Lagos+Urbanos+En+Chile&author=Parra,+O.&author=Baeza,+C.&author=Almanza,+V.&author=Urrutia,+R.&author=Figueroa,+R.&author=Fern%C3%A1ndez,+X.&author=de+Or%C3%BAe,+P.&author=Gonz%C3%A1lez,+P.&author=Beltr%C3%A1n,+J.&author=Becerra,+J.&publication_year=2016&pages=133%E2%80%93146

Parra et al., O. (2003). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*, 51-83. https://ui.adsabs.harvard.edu/abs/2003Limne..22...51P

Parra, O. (2003a). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://doi.org/10.23818/limn.22.04

Parra, O. (2003b). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://www.limnetica.net/documentos/limnetica/limnetica-22-1-p-51.pdf

Parra, O., Basualto, S., Urrutia, R., & Valdovinos, C. (1999). Estudio comparativo de la diversidad fitoplanctónica de cinco lagos de diferentes niveles de eutroficación del área litoral de la región del Biobio (Chile). *Gayana Botánica (Chile)*, *56*, 93-108.

Parra, O. O. (1989). *La eutroficación de la Laguna Grande de San Pedro, Concepción, Chile: Un caso de estudio.*

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005a). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005b). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Pedreros-Guarda, M. (2025). *Github COHERENS Lake*. https://github.com/mpedreros/COHERENS_Lake.git

Pedreros-Guarda, M. (2025). *Mpedreros/TesisDoctoral* [Software]. https://github.com/mpedreros/TesisDoctoral (Obra original publicada en 2025)

Pedreros-Guarda, M., Abarca-del-Río, R., Crétaux, J. F., & Paris, A. (2025). Long-term lake water levels in central Chile using satellite altimetry and conceptual hydrological modelling approaches. *Advances in Space Research*, *76*(4), 1997-2018. https://doi.org/10.1016/j.asr.2025.05.091

Pedreros-Guarda, M., Abarca-del-Río, R., Escalona, K., García, I., & Parra, Ó. (2021). A Google Earth Engine Application to Retrieve Long-Term Surface Temperature for Small Lakes. Case: San Pedro Lagoons, Chile. *Remote Sensing*, *13*(22), 4544. https://doi.org/10.3390/rs13224544

Piccioni, F., Casenave, C., Lemaire, B. J., Le Moigne, P., Dubois, P., & Vinçon-Leite, B. (2021). The thermal response of small and shallow lakes to climate change: New insights from 3D hindcast modelling. *Earth System Dynamics*, *12*(2), 439-456. https://doi.org/10.5194/esd-12-439-2021

Piccolroaz, S., Toffolon, M., & Majone, B. (2013). A simple lumped model to convert air temperature into surface water temperature in lakes. *Hydrology and Earth System Sciences*, *17*(8), 3323-3338. https://doi.org/10.5194/hess-17-3323-2013

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024a). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024b). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Pilla, R. M., Williamson, C. E., Zhang, J., Smyth, R. L., Lenters, J. D., Brentrup, J. A., Knoll, L. B., & Fisher, T. J. (2018). Browning-Related Decreases in Water Transparency Lead to Long-Term Increases in Surface Water Temperature and Thermal Stratification in Two Small Lakes. *Journal of Geophysical Research: Biogeosciences*, *123*(5), 1651-1665. https://doi.org/10.1029/2017JG004321

Pinto, A. P., García, P. B., Almonacid, L. E., & Henríquez, B. J. (2023). Zonas de Sacrificio y Recuperación Socioambiental en Chile: Fallas y oportunidades de la política ambiental. *Ambiente & Sociedade*, *26*, e01371. https://www.scielo.br/j/asoc/a/JdDjvNrLpBJPKwYfppfDBWB/

Prats, J., Reynaud, N., Rebière, D., Peroux, T., Tormos, T., & Danis, P.-A. (2018). LakeSST: Lake Skin Surface Temperature in French inland water bodies for

1999–2016 from Landsat archives. *Earth System Science Data*, *10*(2), 727-743. https://doi.org/10.5194/essd-10-727-2018

Qiao, B., Du, T., Ju, J., & Zhu, L. (2025). Water depth inversion based on ICESat-2 and Sentinel-2—A case study of Qiagui Co and Ayakekumu Lake on the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *59*, 102354. https://doi.org/10.1016/j.ejrh.2025.102354

Quevedo, F., Rojas Hernández, J., & Barra, R. O. (2022). Towards a Chilean Water Governance: A Study on the Los Batros and Paicaví Wetland Reservoirs. *Water*, *14*(18), Article 18. https://www.mdpi.com/2073-4441/14/18/2861

Quintana, J. M., & Aceituno, P. (2012). Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30-43º S. *Atmósfera*, *25*(1), 1-22. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S0187-62362012000100001&lng=es&nrm=iso&tlng=en

Randrianiaina, Rakotonirina, Ratiarimanana, & Lahatra. (2018). *Temperature Retrieval of Lake Itasy Using Remote Sensing*. https://scholar.google.com/scholar_lookup?title=Temperature+Retrieval+of+Lake+Itasy+Using+Remote+Sensing&author=Randrianiaina,+J.&author=Rakotonirina,+I.&author=Ratiarimanana,+R.&author=Lahatra,+F.&publication_year=2018&journal=Resour.+Environ.&volume=8&pages=241%E2%80%93244

Regier, H. A. (1993a). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Regier, H. A. (1993b). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Renting, H., Rossing, W. A. H., Groot, J. C. J., Van der Ploeg, J. D., Laurent, C., Perraud, D., Stobbelaar, D. J., & Van Ittersum, M. K. (2009). Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. *Journal of Environmental Management, Multifunctional agriculture - From farm diagnosis to farm design and institutional innovation*, *90*, S112-S123. https://doi.org/10.1016/j.jenvman.2008.11.014

Restrepo, L. A. V., & Sal, A. G. (2008). Un marco conceptual y analítico para estimar la integridad ecológica a escala de paisaje. *Arbor*, *184*(729), Article 729. https://arbor.revistas.csic.es/index.php/arbor/article/view/159

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Roche, P. K., & Campagne, C. S. (2017). From ecosystem integrity to ecosystem condition: A continuity of concepts supporting different aspects of ecosystem sustainability. *Current Opinion in Environmental Sustainability*, *29*, 63-68. https://www.sciencedirect.com/science/article/pii/S1877343517302828

Rockström, J., Donges, J. F., Fetzer, I., Martin, M. A., Wang-Erlandsson, L., & Richardson, K. (2024). Planetary Boundaries guide humanity's future on Earth. *Nature Reviews Earth & Environment*, *5*(11), 773-788. https://www.nature.com/articles/s43017-024-00597-z

Rojas Quezada, C. A., Muñiz Olivera, I., & García-López, M. Á. (2009). Estructura urbana y policentrismo en el Área Metropolitana de Concepción. *EURE (Santiago)*, *35*(105), 47-70. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0250-71612009000200003&lng=es&nrm=iso&tlng=es

Rutllant, J., & Fuenzalida, H. (1991). Synoptic aspects of the central chile rainfall variability associated with the southern oscillation. *International Journal of Climatology*, *11*(1), 63-76. https://doi.org/10.1002/joc.3370110105

Salazar, Á., Thatcher, M., Goubanova, K., Bernal, P., Gutiérrez, J., & Squeo, F. (2024). CMIP6 precipitation and temperature projections for Chile. *Climate Dynamics*, *62*(3), 2475-2498. https://doi.org/10.1007/s00382-023-07034-9

Saloranta, T. M., & Andersen, T. (2007). MyLake—A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations. *Ecological Modelling, Uncertainty in Ecological Models*, *207*(1), 45-60. https://doi.org/10.1016/j.ecolmodel.2007.03.018

San Llorente Capdevila, A., Kokimova, A., Sinha Ray, S., Avellán, T., Kim, J., & Kirschke, S. (2020). Success factors for citizen science projects in water quality monitoring. *Science of The Total Environment*, *728*, 137843. https://doi.org/10.1016/j.scitotenv.2020.137843

Saraceni, M., Brunone, B., Silvestri, L., Meniconi, S., & Cerlini, P. B. (2025). *A Water Mass Balance–Based Procedure Using ERA5 Land Reanalysis and Level Observation to Reconstruct the Past Level Changes of Closed Lakes toward Future Management*. https://doi.org/10.1175/JHM-D-24-0019.1

Sarkar, D., Kar, S. K., Chattopadhyay, A., Shikha, Rakshit, A., Tripathi, V. K., Dubey, P. K., & Abhilash, P. C. (2020). Low input sustainable agriculture: A viable climate-smart option for boosting food production in a warming world. *Ecological Indicators*, *115*, 106412. https://www.sciencedirect.com/science/article/pii/S1470160X20303496

Sarkar, S., & Maity, R. (2021). Global climate shift in 1970s causes a significant worldwide increase in precipitation extremes. *Scientific Reports*, *11*(1), 11574. https://doi.org/10.1038/s41598-021-90854-8

Sarricolea, P., Herrera-Ossandon, M., & Meseguer-Ruiz, Ó. (2017). Climatic regionalisation of continental Chile. *Journal of Maps*, *13*(2), 66-73. https://doi.org/10.1080/17445647.2016.1259592

Sazib, N., Mladenova, I., & Bolten, J. (2018). Leveraging the Google Earth Engine for Drought Assessment Using Global Soil Moisture Data. *Remote Sensing*, *10*(8), Article 8. https://doi.org/10.3390/rs10081265

Schallenberg, M., de Winton, M. D., & Kelly, D. J. (2018). Indicators of Ecological Integrity. En D. P. Hamilton, K. J. Collier, J. M. Quinn, & C. Howard-Williams (Eds.), *Lake Restoration Handbook: A New Zealand Perspective* (pp. 367-393). Springer International Publishing. https://doi.org/10.1007/978-3-319-93043-5_11

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591-596. https://doi.org/10.1038/35098000

Schmid, M., & Read, J. (2022). Heat budget of lakes. En *Encyclopedia of inland waters* (Vol. 1, pp. 467-473). https://doi.org/10.1016/b978-0-12-819166-8.00011-6

Schmithuesen, F. (2007). Multifunctional forestry practices as a land use strategy to meet increasing private and public demands in modern societies. *Journal of Forest Science - UZPI (Czech Republic)*, *53*(6). https://agris.fao.org/search/en/providers/122644/records/647247a2e17b74d2224f615d

Schott, F. A., Wang, W., & Stammer, D. (2007). Variability of Pacific subtropical cells in the 50-year ECCO assimilation. *Geophysical Research Letters*, *34*(5). https://doi.org/10.1029/2006GL028478

Schwatke, C., Dettmering, D., Bosch, W., & Seitz, F. (2015). DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrology and Earth System Sciences*, *19*(10), 4345-4364. https://doi.org/10.5194/hess-19-4345-2015

Seidl, R., & Barthel, R. (2017). Linking scientific disciplines: Hydrology and social sciences. *Journal of Hydrology*, *550*, 441-452. https://doi.org/10.1016/j.jhydrol.2017.05.008

Shao, G. P., & Bishop, I. J. (2025). Citizen science in river monitoring: A systematic literature review of the whys and hows. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1609084

Shchepetkin, A. F., & McWilliams, J. C. (2003). A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. *Journal of Geophysical Research: Oceans*, *108*(C3). https://doi.org/10.1029/2001JC001047

Shine, K. P. (1984). Parametrization of the shortwave flux over high albedo surfaces as a function of cloud thickness and surface albedo. *Quarterly Journal of the Royal Meteorological Society*, *110*(465), 747-764. https://doi.org/10.1002/qj.49711046511

Simon, D. F., Munoz, G., Dinh, Q. T., Duy, S. V., Kavanagh, K., Smith, R., Husk, B., & Sauvé, S. (2023). Adopt a Lake: Successfully Tracking Harmful Cyanobacterial Blooms in Canadian Surface Waters Through Citizen Science. *Citizen Science: Theory and Practice*, *8*(1). https://doi.org/10.5334/cstp.655

Smagorinsky, J. (1963). *GENERAL CIRCULATION EXPERIMENTS WITH THE PRIMITIVE EQUATIONS*. https://journals.ametsoc.org/view/journals/mwre/91/3/1520-0493_1963_091_0099_gcewtp_2_3_co_2.xml

Smith, L. T. (2016). *A descolonizar las metodologías. Investigación y pueblos indígenas: A descolonizar las metodologías. Investigación y pueblos indígenas*. LOM Ediciones.

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, *10*(2), 126-139. https://doi.org/10.1065/espr2002.12.142

Sobarzo, M. B., Figueroa, D., & Arcos, D. R. (1997). The Influence of Winds and Tides in the Formation of Circulation Layers in a Bay, a Case Study: Concepción Bay, Chile. *Estuarine, Coastal and Shelf Science*, *45*(6), 729-736. https://doi.org/10.1006/ecss.1997.0233

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. *Anthropocene Review*, *2*(1), 81-98. http://www.scopus.com/inward/record.url?scp=84996501052&partnerID=8YFLogxK

Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., & Mironov, D. (2010). First steps of a lake model intercomparison project: LakeMIP. *Boreal environment research*, *15*(2), 191. https://search.proquest.com/openview/d60a3674e3599840e062b6afc6aff527/1?pq-origsite=gscholar&cbl=5500736

Suazo, B. (2014). Fragmentación socioespacial en el barrio Boca Sur, San Pedro de la Paz: La necesidad de implementar una planificación participativa. *Universidad de Concepción*.

Sullivan, C. J., Read, J. S., & Hansen, G. J. A. (2025). Climate-driven alterations of lake thermal regimes. *Limnology and Oceanography*, *70*(8), 2348-2364. https://doi.org/10.1002/lno.70128

Sultana, F. (2022). Critical climate justice. *The Geographical Journal*, *188*(1), 118-124. https://onlinelibrary.wiley.com/doi/abs/10.1111/geoj.12417

Szesztay, K. (1974). Water balance and water level fluctuations of lakes. *Hydrological Sciences Bulletin*, *19*(1), 73-84. http://www.tandfonline.com/doi/abs/10.1080/02626667409493872

Tachikawa, T., Hato, M., Kaku, M., & Iwasaki, A. (2011). Characteristics of ASTER GDEM version 2. *2011 IEEE International Geoscience and Remote Sensing Symposium*, 3657-3660. https://doi.org/10.1109/IGARSS.2011.6050017

Taghizadeh, E., Ahmadi-Givi, F., Brocca, L., & Sharifi, E. (2021). Evaluation of satellite/reanalysis precipitation products over Iran. *International Journal of Remote Sensing*, *42*(9), 3474-3497. https://doi.org/10.1080/01431161.2021.1875508

Tavares, M. H., Cunha, A. H. F., Motta-Marques, D., Ruhoff, A. L., Cavalcanti, J. R., Fragoso, C. R., Martín Bravo, J., Munar, A. M., Fan, F. M., & Rodrigues, L. H. R. (2019). Comparison of Methods to Estimate Lake-Surface-Water Temperature Using Landsat 7 ETM+ and MODIS Imagery: Case Study of a Large Shallow Subtropical Lake in Southern Brazil. *Water*, *11*(1), Article 1. https://doi.org/10.3390/w11010168

Tedesco, A. M., López-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Pérez-Hämmerle, K.-V., Brancalion, P. H. S., Wilson, K. A., Oliveira, M., Correa, D. F., Ota, L., Morrison, T. H., Possingham, H. P., Mills, M., Santos, F. C., & Dean, A. J. (2023). Beyond ecology: Ecosystem restoration as a process for social-ecological transformation. *Trends in Ecology & Evolution*, *38*(7), 643-653. https://doi.org/10.1016/j.tree.2023.02.007

Tierney, G. L., Faber-Langendoen, D., Mitchell, B. R., Shriver, W. G., & Gibbs, J. P. (2009). Monitoring and evaluating the ecological integrity of forest ecosystems. *Frontiers in Ecology and the Environment*, *7*(6), 308-316. https://doi.org/10.1890/070176

Tilgenkamp, A. (2025, agosto 2). *Theil–Sen estimator [online]. MATLAB Central File Exchange.* https://www.mathworks.com/matlabcentral/fileexchange/34308-theil-sen-estimator

Torres, R. (2023, enero 24). Resistance In Chile's "State Of Exception". *Majority Post*. https://majoritypost.com/resistance-in-chiles-state-of-exception/

Torres, R., Azócar, G., Gallardo, R., & Mendoza, J. (2022). *Water Extractivism and Decolonial Struggles in Mapuche Territory, Chile*. *15*(1).

Torres, R., Azócar, G., Rojas, J., Montecinos, A., & Paredes, P. (2015). Vulnerability and resistance to neoliberal environmental changes: An assessment of

agriculture and forestry in the Biobio region of Chile (1974–2014). *Geoforum*, *60*, 107-122. https://doi.org/10.1016/j.geoforum.2014.12.013

Traganos, D., Poursanidis, D., Aggarwal, B., Chrysoulakis, N., & Reinartz, P. (2018). Estimating Satellite-Derived Bathymetry (SDB) with the Google Earth Engine and Sentinel-2. *Remote Sensing*, *10*(6), Article 6. https://doi.org/10.3390/rs10060859

Trenberth, K. E., & Hoar, T. J. (1996). The 1990–1995 El Niño-Southern Oscillation Event: Longest on Record. *Geophysical Research Letters*, *23*(1), 57-60. https://doi.org/10.1029/95GL03602

Troitskaya, Y., Rybushkina, G., Soustova, I., Balandina, G., Lebedev, S., & Kostianoy, A. (2012). Adaptive retracking of Jason-1 altimetry data for inland waters: The example of the Gorky Reservoir. *International Journal of Remote Sensing*, *33*(23), 7559-7578. https://doi.org/10.1080/01431161.2012.685972

UCM. (2024). *Earth Engine Data Catalog: TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces [online]. Merced, University of California Merced.* https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE#bands

University of North Carolina. (2025). *Mediciones en Lagos Red Ciudadana y Satelital*. LOCSS. https://www.locss.org/es

Upreti, G. (2023). Autopoiesis, Organizational Complexity, and Ecosystem Health. En G. Upreti (Ed.), *Ecosociocentrism: The Earth First Paradigm for Sustainable Living* (pp. 91-110). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-41754-2_5

Urrutia, R., Almanza, V., & Woelfl, S. (2022, septiembre 8). *Seminario proyecto: Levantamiento de información limnológica para la propuesta de NSCA de lagos nor-patagónicos* [[Discurso principal]. Seminario en línea.].

US EPA. (2011). *National wetland condition assessment: Field operations manual*.

US EPA. (2025). *Factsheets on Water Quality Parameters*. https://www.epa.gov/awma/factsheets-water-quality-parameters

US EPA, O. (2015, abril 16). *What is the National Lakes Assessment?* [Overviews and Factsheets]. https://www.epa.gov/national-aquatic-resource-surveys/what-national-lakes-assessment

USGS. (2025). *U.S. Geological Survey*. https://www.usgs.gov/

Valdés-Pineda, R., Cañón, J., & Valdés, J. B. (2018). Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals. *Journal of Hydrology*, *556*, 1153-1170. https://doi.org/10.1016/j.jhydrol.2017.01.031

Valdés-Pineda, R., Valdés, J. B., Diaz, H. F., & Pizarro-Tapia, R. (2016, junio 30). *Analysis of spatio-temporal changes in annual and seasonal precipitation variability in South America-Chile and related ocean-atmosphere circulation patterns.* | *EBSCOhost*. https://doi.org/10.1002/joc.4532

Vela, S. R. (2019). Método mayéutica y consultorías filosóficas en el siglo XXI. *Phainomenon*, *18*(2), 141-154. https://doi.org/10.33539/phai.v18i2.1745

Vera, R., & Rosner, C. (2020). *Recopilación y análisis de antecedentes para la revisión de la Norma Secundaria de Calidad Ambiental del lago Llanquihue*. ResearchGate. https://doi.org/10.13140/RG.2.2.29431.80801

Vergara Díaz, G., Vázquez, V. S., & Herrera Machuca, M. Á. (2018). Análisis del ambio temporal y espacial del uso del suelo en la región Centro-sur de Chile. *Ciência Florestal*, *28*, 1831-1844.

https://www.scielo.br/j/cflo/a/rtg7y6cGShDvQkMjWL7k47Q/?lang=es&format=html&stop=next
Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). *A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index*. https://doi.org/10.1175/2009JCLI2909.1
Vlasova, T., Petrov, A. N., & Volkov, S. (2021). Rethinking Sustainability Monitoring in the Arctic by Linking Resilience and Sustainable Development in Socially-Oriented Observations: A Perspective. *Sustainability*, *13*(1), Article 1. https://doi.org/10.3390/su13010177
Voulvoulis, N., Giakoumis, T., Hunt, C., Kioupi, V., Petrou, N., Souliotis, I., Vaghela, C., & binti Wan Rosely, WIH. (2022). Systems thinking as a paradigm shift for sustainability transformation. *Global Environmental Change*, *75*, 102544. https://www.sciencedirect.com/science/article/pii/S0959378022000826
Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., & Bierkens, M. F. P. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, *37*(20). https://doi.org/10.1029/2010GL044571
Wadoux, A. M. J.-C., & Minasny, B. (2024). Some limitations of the concordance correlation coefficient to characterise model accuracy. *Ecological Informatics*, *83*, 102820. https://doi.org/10.1016/j.ecoinf.2024.102820
Wakana, I., Kadono, Y., Urabe, J., Tamura, Y., Suzuki, Y., Yamada, H., Oyama, Y., Wada, K., Hasegawa, T., & Ohara, M. (2023). Varying stages of ecological succession in lakes subdivided by volcanic eruptions at Akan Caldera, Japan. *Hydrobiologia*, *850*(18), 3919-3933. https://doi.org/10.1007/s10750-023-05231-5
Wang, H., Qi, Y., Lian, X., Zhang, J., Yang, R., & Zhang, M. (2022). Effects of climate change and land use/cover change on the volume of the Qinghai Lake in China. *Journal of Arid Land*, *14*(3), 245-261. https://doi.org/10.1007/s40333-022-0062-4
Warner, S., Blanco Ramírez, S., de Vries, S., Marangu, N., Ateba Bessa, H., Toranzo, C., Imaralieva, M., Abrate, T., Kiminta, E., Castro, J., de Souza, M. L., Ghaffar Memon, A., Loiselle, S., & Juanah, M. S. E. (2024). Empowering citizen scientists to improve water quality: From monitoring to action. *Frontiers in Water*, *6*. https://doi.org/10.3389/frwa.2024.1367198
Westra, L., & Lemons, J. (2012). *Perspectives on Ecological Integrity*. Springer Science & Business Media.
Wetzel, R. G. (2001). *Limnology: Lake and River Ecosystems*. Gulf Professional Publishing.
Williams, J. (2021). *Climate change is racist: Race, privilege and the struggle for climate justice*. Icon Books. https://books.google.es/books?hl=es&lr=&id=RIQiEAAAQBAJ&oi=fnd&pg=PP8&dq=Williams,+J.+(2021).+Climate+change+is+racist:+Race,+privilege+and+the+struggle+for+climate+justice.+Icon+Books.&ots=NWw2BQCCgc&sig=7BuVe4PrQpNz7d1MptUcKTYDbj4
Willmott, C. J. (1981). On the Validation of Models. *Physical Geography*, *2*(2), 184-194. https://doi.org/10.1080/02723646.1981.10642213
Winkler, K., Fuchs, R., Rounsevell, M., & Herold, M. (2021). Global land use changes are four times greater than previously estimated. *Nature Communications*, *12*(1), 2501. https://www.nature.com/articles/s41467-021-22702-2

Winter, T. C. (1981). Uncertainties in Estimating the Water Balance of Lakes. *JAWRA Journal of the American Water Resources Association*, *17*(1), 82-115. https://doi.org/10.1111/j.1752-1688.1981.tb02593.x

WISDOM. (2025). *Objectives of the WISDOM Project*. https://wisdom.eoc.dlr.de/en/content/objectives-wisdom-project.html

WMO. (2025). *WMO Information System (WIS)*. https://old.wmo.int/extranet/pages/prog/www/WIS/

WMOa. (2025). *Observing Systems Capability Analysis and Review Tool (OSCAR)*. https://oscar.wmo.int/surface/#/

Wolodarsky-Franke, A., & Díaz, S. (2011). Cordillera de Nahuelbuta. *Reserva Mundial de Biodiversidad. Valdivia, Chile: WWF*.

Wongchuig, S., Carlo Espinoza, J., Condom, T., Junquas, C., Sierra, J. P., Fita, L., Sörensson, A., & Polcher, J. (2023). Changes in the surface and atmospheric water budget due to projected Amazon deforestation: Lessons from a fully coupled model simulation. *Journal of Hydrology*, *625*, 130082. https://doi.org/10.1016/j.jhydrol.2023.130082

Woods, S. (2025). How citizen science can help to solve the global freshwater crisis. *Nature*, *644*(8077), 582-582. https://doi.org/10.1038/d41586-025-02614-7

Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews Earth & Environment*, *1*(8), 388-403. https://doi.org/10.1038/s43017-020-0067-5

Woolway, R. I., Sharma, S., & Smol, J. P. (2022). Lakes in Hot Water: The Impacts of a Changing Climate on Aquatic Ecosystems. *BioScience*, *72*(11), 1050-1061. https://doi.org/10.1093/biosci/biac052

Woolway, R. I., Tong, Y., Feng, L., Zhao, G., Dinh, D. A., Shi, H., Zhang, Y., & Shi, K. (2024). Multivariate extremes in lakes. *Nature Communications*, *15*(1), 4559. https://doi.org/10.1038/s41467-024-49012-7

Wu, J., Li, W., Du, H., Wan, Y., Yang, S., & Xiao, Y. (2025). Nonlinear responses of coupled socioecological systems to land use and climate changes in the Yangtze river basin. *Scientific Reports*, *15*(1), 6940. https://doi.org/10.1038/s41598-025-92084-8

Wurtsbaugh, W. A., Paerl, H. W., & Dodds, W. K. (2019). Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *WIREs Water*, *6*(5), e1373. https://doi.org/10.1002/wat2.1373

Xu, J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Xu, W. (2022). Ecological Integrity Evaluation of Organically Evolved Cultural Landscape. *Mobile Information Systems*, *2022*(1), 9554359. https://doi.org/10.1155/2022/9554359

Xu (徐菊英), J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Yang, J., & Du, X. (2017). An enhanced water index in extracting water bodies from Landsat TM imagery. *Annals of GIS*, *23*(3), 141-148. https://doi.org/10.1080/19475683.2017.1340339

Yang, Xu, M., Li, R., Zhang, L., & Deng, Q. (2020). Estimating the ecological water levels of shallow lakes: A case study in Tangxun Lake, China. *Scientific Reports*, *10*(1), 5637. https://doi.org/10.1038/s41598-020-62454-5

Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J.-F., Wada, Y., & Berge-Nguyen, M. (2023). Satellites reveal widespread decline in global lake water storage. *Science*, *380*(6646), 743-749. https://doi.org/10.1126/science.abo2812

Zelený, J., Mercado-Bettín, D., & Müller, F. (2021). Towards the evaluation of regional ecosystem integrity using NDVI, brightness temperature and surface heterogeneity. *Science of The Total Environment*, *796*, 148994. https://www.sciencedirect.com/science/article/pii/S0048969721040663

Zhang, M., Lee, H., SHUM, C. K., Alsdorf, D., Schwartz, F., Tseng, K.-H., Yi, Y., Kuo, C.-Y., Tseng, H.-Z., Braun, A., Calmant, S., Filizola, N., & Seyler, F. (2010). Application of retracked satellite altimetry for inland hydrologic studies. *International Journal of Remote Sensing*, *31*(14), 3913-3929. https://doi.org/10.1080/01431161.2010.483495

Zhao, G., Li, Y., Zhou, L., & Gao, H. (2022). Evaporative water loss of 1.42 million global lakes. *Nature Communications*, *13*(1), 3686. https://doi.org/10.1038/s41467-022-31125-6

Zhao, Y., Feng, D., Yu, L., Wang, X., Chen, Y., Bai, Y., Hernández, H. J., Galleguillos, M., Estades, C., Biging, G. S., Radke, J. D., & Gong, P. (2016). Detailed dynamic land cover mapping of Chile: Accuracy improvement by integrating multi-temporal data. *Remote Sensing of Environment*, *183*, 170-185. https://www.sciencedirect.com/science/article/pii/S0034425716302188

Zhou, J., Leavitt, P. R., Rose, K. C., Wang, X., Zhang, Y., Shi, K., & Qin, B. (2023). Controls of thermal response of temperate lakes to atmospheric warming. *Nature Communications*, *14*(1), 6503. https://doi.org/10.1038/s41467-023-42262-x

Zhu, J., Peng, S., Shen, X., Lin, Z., Gong, L., Zhang, R., & Huang, B. (2024). Multiple scale impacts of land use intensity on water quality in the Chishui river source area. *Ecological Indicators*, *166*, 112396. https://doi.org/10.1016/j.ecolind.2024.112396

Zhu, L., Ju, J., Qiao, B., Liu, C., Wang, J., Yang, R., Ma, Q., Guo, L., & Pang, S. (2025). Physical and biogeochemical responses of Tibetan Plateau lakes to climate change. *Nature Reviews Earth & Environment*, *6*(4), 284-298. https://doi.org/10.1038/s43017-025-00650-5

Capítulo V

Long-term Lake Water Levels in Central Chile Using Satellite Altimetry and Conceptual Hydrological Modelling Approaches

Chapter based on the article: Pedreros-Guarda, M., Abarca-del-Río, R., Crétaux, J. F., & Paris, A. (2025). Long-term Lake Water Levels in Central Chile Using Satellite Altimetry and Conceptual Hydrological Modelling Approaches. *Advances in Space Research*. https://doi.org/10.1016/j.asr.2025.05.091

Abstract

Lakes play a vital role in biodiversity conservation and water regulation but are increasingly affected by climate change and human activity. Despite their importance, long-term water level (WL) records remain scarce for most lakes in the Southern Hemisphere. This study introduces a novel conceptual modeling framework for reconstructing WL dynamics, applied to Lake Lanalhue in south-central Chile over the period 1950–2022. The approach integrates satellite altimetry (Sentinel-3A), validated against in-situ WL data, with global hydroclimatic datasets (ERA5-Land, GLEV, TerraClimate).

Validation against altimetric records (2016–2023) shows strong agreement (R^2 = 0.71; *NRMSE* = 0.11 m). Precipitation emerges as the dominant seasonal driver (R^2 = 0.86), while evaporation exerting a lagged secondary influence (R^2 = 0.67). Climate oscillations modulate variability across distinct temporal scales: ENSO drives high-frequency interannual fluctuations (R = 0.37), while the Antarctic Oscillation (AAO) governs lower-frequency variability (≥5 years; R = 0.60–0.64). A long-term WL decline of ~5 mm per year is attributed to reduced precipitation and regional warming, amplified by AAO-related circulation changes. The proposed framework offers a scalable, low-cost tool for reconstructing water levels in under-monitored lakes, supporting climate adaptation, environmental management, and long-term hydrological monitoring in remote, data-scarce regions.

1. Introduction

Lake ecosystems support vast biodiversity (G. Zhao et al., 2022) and play a crucial role in the water cycle, providing storage, natural filtration, groundwater recharge, and mitigation of floods and droughts (Crétaux et al., 2016; McGregor, 2017). However, lakes face significant environmental stress due to climate-related factors and human activities, which affect the hydrologic integrity of the lake's basins and ecosystems (He et al., 2000; Oxley, 2015). Climate change, primarily driven by human activities (G. Hansen & Stone, 2016; Haustein et al., 2017), has altered both global and local climate regimes,

particularly since the 1970s (Jacques Coper & Garreaud Salazar, 2015; S. Sarkar & Maity, 2021). Lakes are highly sensitive to climate changes, particularly in terms of alterations in water quality (L. Zhu et al., 2025) and quantity (Woolway et al., 2020). Over the past few decades, water levels in many lakes worldwide have significantly declined, with some lakes even drying out completely (Wang et al., 2022; Woolway et al., 2020; Yao et al., 2023).

Ecosystems transition from a state of health to degradation when subjected to anthropogenic stress (Holling, 1986; Regier, 1993b). Restoration efforts aim to move the systems towards a state of more integrity (Mayer & Rietkerk, 2004). To support these efforts, defining a reference state of the system is important and requires historical reconstruction (Zelený et al., 2021). Hydrologically, lake water levels serve as a key variable that can help reconstruct the hydrologic dynamics of lakes. The alteration of the water level of a lake is studied with respect to a natural or reference condition (Marttunen et al., 2006).

In this work, the study of water level is framed within a set of indicators that reflect the hydrological integrity of a basin. That is, they allow us to collectively assess the state or condition of a system with respect to its hydro physical dimension. This is a key dimension in water management. It allows us to assess impacts such as floods and droughts.

As precedents for this around the world, there is an example in Finland: the Finnish Institute of Environment developed a water level analysis model for Finnish lakes. Thanks to this, there are around 30 water level indicators that characterize the ecosystem impact of lake level fluctuations (Y. Gao et al., 2020). Examples of these indicators are: monthly water level, flood duration, flood timing, and water level drops at different elevations (Y. Gao et al., 2020). Another example is the WISDOM Project, a bilateral research initiative between Germany and Vietnam that focuses on developing a comprehensive water information system for the Mekong Delta. The project emphasizes the quantification of water resources, including water levels, floods, minimum flows, water availability, and patterns of water use (WISDOM, 2025). In South America there is the Amazon Basin Project, that brings together the eight member countries (Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela) of the Amazon Cooperation Treaty Organization, to establish an Integrated Water Resources Monitoring System. Central to this initiative are the Amazon Hydrometeorological Network (AHN), which measures water levels, flow rates, and rainfall, and the Regional Water Quality Network (WQN), which monitors water quality through specialized laboratories. Together, these networks provide consistent regional data to strengthen basin management, cooperation, and resilience against extreme events (Organización del Tratado de Cooperación Amazónica, 2025).

This chapter intends to develop a scalable methodology to retrieve long-term water levels, as a mean to understand historical hydrological degradation, but also in order to validate altimetric methods to monitor lake water levels as a key indicator for hydrological integrity.

In a lake basin, water levels (WL) reflect the hydrologic regime of the entire basin (Crétaux et al., 2016) and serve as key indicators of both climate change and land use/cover change (LUCC) (Mason et al., 1994; Wang et al., 2022). Climatic forcing can affect lakes on interseasonal, interannual, interdecadal, or secular scales (Mason et al., 1994). In simple terms, climate change reduces precipitation, leading to decreased runoff, while rising air temperature and evaporation, further decreasing runoff (Argyilan & Forman, 2003; Little et al., 2009; Mason et al., 1994; G. Zhao et al., 2022). Around the world, the response of lakes level to climatic forcing is often studied by examining atmospheric teleconnections, as well as long-term patterns of precipitation, temperature, wind, solar radiation and humidity, among others (McGregor, 2017).

Despite the need for continuous monitoring and historic reconstruction, in-situ data on water levels are often scarce or entirely lacking in South America. Satellite altimetry and hydroclimatic databases can fill this gap and play a crucial role in lake monitoring (Abarca-Del-Rio et al., 2012; Condom et al., 2020). Advanced remote sensing technology, particularly satellite altimetry, has been widely adopted for monitoring lake levels in regions where

hydrological station data are unavailable (Wang et al., 2022). In addition, satellite radar altimetry systems are actively used for lake monitoring in Europe, the USA, China, and India (Crétaux et al., 2016). There are also space based-laser altimeters (ICESat-2, Jung et al. 2025) which has proven useful in the retrieval of inland water level (Kaya, 2025; Kaya et al., 2025) and bathymetry (Arsen et al., 2014; Qiao et al., 2025).

Satellite radar altimetry was originally developed in the 1970s to study the spatial and temporal variability of ocean surface height (also called sea level, SL). Nowadays, instantaneous height measurements by satellites have broadened towards inland water bodies with an accuracy of a few centimetres (CNES, 2015). While this technology was initially applied for large lakes (Crétaux & Birkett, 2006), numerous studies over the past 30 years have demonstrated that radar altimetry can measure WL with accuracy ranging from a few centimetres for large lakes to a few decimetres for smaller lakes and rivers (Crétaux et al., 2011; Gao et al., 2012; Schwatke et al., 2015). Recent studies have also shown that new algorithmic developments allow for measurements with centimeter-level accuracy even in small lakes (Boy et al., 2022; Frappart et al., 2021).

Satellite radar altimetry has continuously provided measurements since the early 1990s, through two successive generations of satellite families since then: i) the ERS-1, ERS-2, Envisat and Saral series, and ii) the Topex/Poseidon, Jason-1, 2 and 3 series and Sentinel-6. Several other

satellites, including GFO, HY-2A and particularly Cryosat-2, have also been launched during this period (CNES, 2015). The satellites from the ESA Copernicus program, Sentinel-3A (S3A) and Sentinel-3B (ESA), launched in February 2016 and 2018, respectively, and SWOT (Surface Water and Ocean Topography) in December 2022 (NASA SWOT, 2024), extend these long orbits with new observations (SAT altimeter for S3 and Swath altimeter for SWOT).

Although it is an innovative and useful tool, satellite altimetry has only enabled continuous reconstruction of lake levels since the 1990s (CNES, 2015). By incorporating hydroclimatic databases, many of which are publicly available and globally accesible (Condom et al., 2020) it is possible to close the WB of a lake and gain a comprehensive understanding of the factors modulating its levels. An extensive collection of long-term climate datasets is available, including those that interpolate data from surface observations (e.g. WorldClim, CRU), reanalysis datasets (e.g. ERA5, ERA5-Land), and combined sources (e.g. TerraClimate, GLEV) (Abatzoglou et al., 2018).

Most long-term reconstructions of inland WL and discharges dating back to the 1950s, rely on hydrological models, which, while relatively complex, remain the most reliable method recognized to date (Hou et al., 2022). Examples include MGB (Wongchuig et al., 2023), SWAT (L. Zhu et al., 2025) and GBEHM (geomorphology-based ecohydrological model) (Jian et al., 2017). In contrast, several studies have directly retrieved lake water levels from

altimetry for more recent periods (starting from the 2000s), using satellites such as TOPEX/POSEIDON (Abarca-Del-Rio et al., 2012; Cretaux et al., 2005; Ndehedehe et al., 2017; Zhang et al., 2010), Jason (Troitskaya et al., 2012), Envisat (Abarca-Del-Rio et al., 2012; Da Silva et al., 2012; K. Lee et al., 2022) and ICESat and CryoSat products (Cheng et al., 2023). This study fills a critical gap in the Southern Hemisphere, where in-situ lake observations are sparse, by presenting one of the first reconstruction of long-term lake water levels since 1950, using a simple conceptual modelling approach driven by Sentinel-3A altimetry and publicly available hydroclimatic datasets (ERA5-Land, ERA5, TerraClimate and GLEV), without relying on complex hydrological models. This novel, low cost and replicable framework is applied to Lake Lanalhue in the period 1950-2022. It is the only Nahuelbutan lake with historical level records. To validate model performance against observed data and demonstrate its potential for reconstructing water levels in other medium and small lakes lacking in-situ observations. Our approach is designed to be easily applicable to similar glacier-free, medium and small-sized lakes worldwide. While higher-resolution models such as the Weather Research and Forecasting (WRF) combined with a hydrological model (Fustos-Toribio et al., 2022) could be used, our focus is on ensuring the methodology is reproducible. For this reason, we exclusively selected public and global datasets, contributing to the democratization of knowledge.

The first step is to understand the seasonal cycle of WL in Lake Lanalhue, our study area, which serves as a key indicator of the region's hydrological response to climatic forcing. This cycle is driven by a complex interplay of factors, including precipitation, evaporation, and runoff, all of which vary significantly throughout the year. Understanding this seasonal cycle allows us to calibrate the conceptual model and accurately reconstruct long-term variability. We further examine the influence of climatic factors, such as the El Niño-Southern Oscillation (ENSO) (Barría et al., 2021; Garreaud et al., 2009), the Antarctic Oscillation (AAO) (Quintana & Aceituno, 2012), and the Pacific Decadal Oscillation (PDO) (Valdés-Pineda et al., 2018), on the interannual and long-term variability of lake levels. This analysis provides an interpretation of long-term lake WL changes within the context of climatic forcings and noteworthy central-Chile Megadrought (2010-ongoing). By filling the data gap in the Nahuelbuta region, this study offers critical insights into the seasonal and long-term hydrological dynamics of Lake Lanalhue, as well as a reconstruction of conditions before the surge in climate change around 1950 (Lewis & Maslin 2015). The work is organized into six sections: i) Study area (Section 2.), where we outline the ecosystem functioning in relation to the local water cycle. ii) Methodology (Section 3.), which details the data, methods, and work strategy used. iii) Results (Section 4.), where we present the long-term WL of Lake Lanalhue. iv) Discussion (Section 5.), where we interpret these WL records in the context of the region’s climatic history since 1950; and v) Conclusions (Section 6.), summarizing the key findings of this study.

Through this work, this chapter aims to achieve the fourth objective of the present doctoral thesis: analyze the temporal dynamics of water quantity in a Nahuelbutan lake (Lake Lanalhue) from 1950 onwards, using lake water level as the main indicator. It also serves to test the second and third hypotheses: H2: The degradation of nature is manifested in changes to the water cycle and the degradation of its quality. H3: Remote sensing and numerical modeling tools can be integrated into environmental monitoring.

2. Study area

Lake Lanalhue is located in the Biobío region of south-central Chile, near the Pacific Ocean (Figure V.1). This region is characterized by a warm summer Mediterranean climate (Kottek et al., 2006). Lake Lanalhue is part of several small, exorheic coastal basins that drain the western slope of the Nahuelbuta mountain range, therein known as the Nahuelbutan lakes, which are lentic systems defined by their base level. These lakes share climatic and geological characteristics and do not experience winter ice cover (O. Parra, 2003b). The Nahuelbuta mountain range has historically served as a biodiversity reserve during past climate changes, and it continues to hold potential as a refuge under current climate pressures (Wolodarsky-Franke & Díaz, 2011). It is situated in central Chile, a global biodiversity hotspot and a priority conservation site (Arroyo, 2006).

To give some context of the study area, the environmental history of Nahuelbutan lakes can be traced through several key phases: i) 1850-1880: Clearing and burning of native forest for agriculture (Otero Durán, 2012). ii) Post-1974: Forestry plantations expansion exacerbated through Decree Law No. 701 (Aguayo et al., 2009; Araya, 2019; Lara et al., 2012; Martínez Retureta, 2021). iii) Since 1975: Urban development, particularly around Concepción (Rojas Quezada et al., 2009). Key physical, ecological and environmental characteristics of Lake Lanalhue are summarized in Table II.1.

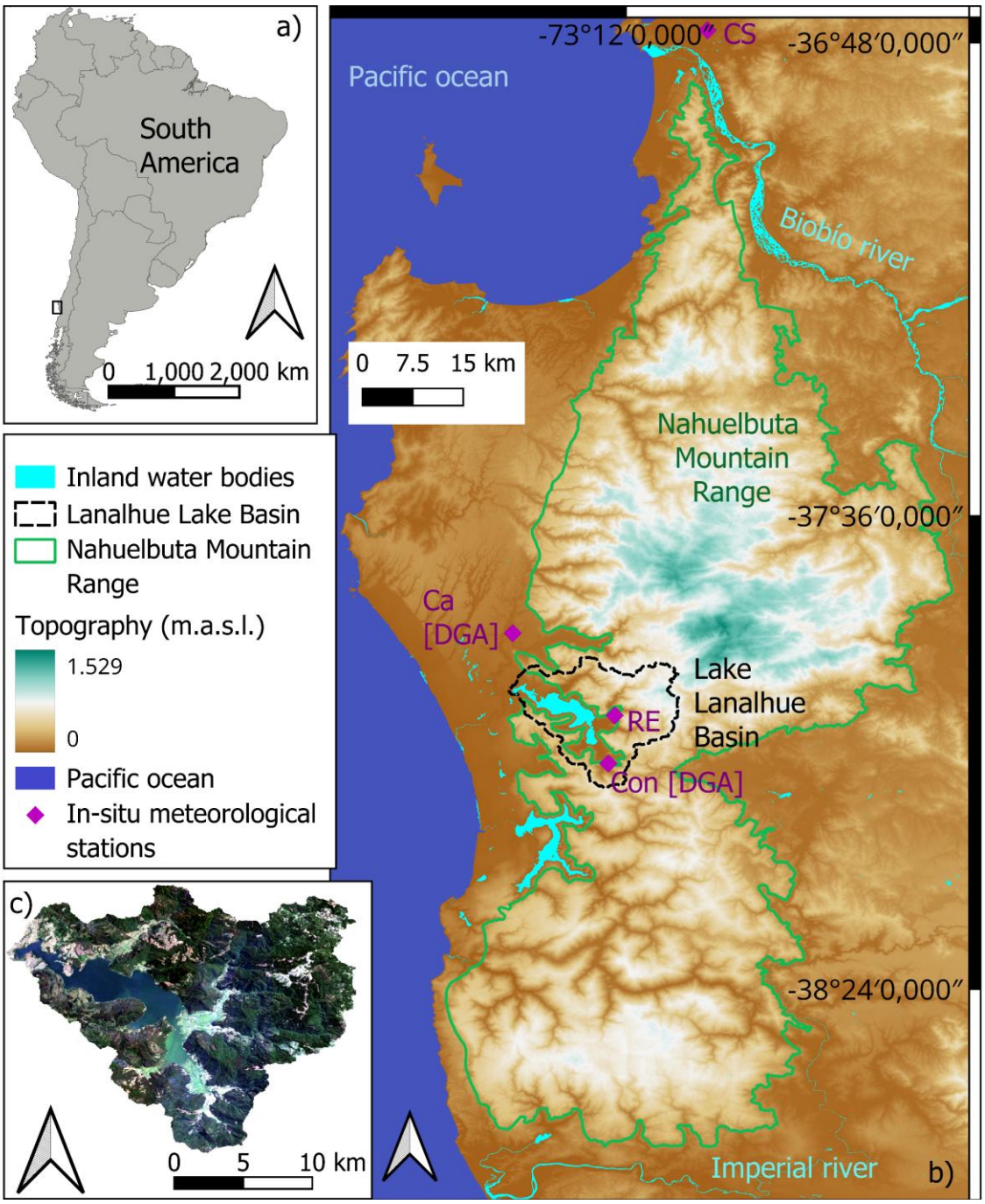


Figure V.1. Study area. a) Location in South America. b) Topography of the area around Lake Lanalhue and in-situ meteorological stations: Cañete (Ca) [DGA], Contulmo (Con) [DGA], Carriel Sur (CS), Río Elicura (RE) at puente Elicura [DGA]. c) RGB Composite of the Lake Lanalhue basin.

Table V.1. Main physical, ecological and environmental characteristics of Lake Lanalhue (Almanza et al., 2016; O. Parra et al., 1999; O. Parra, 2003b; O. Parra et al., 2005a).

Characteristic	Description/value
Lake area (km²)	31.9
Basin area (km²)	327.43
(Basin area / lake area) ratio	10.2
Max length (km)	9.6
Max width (km)	4.3
Mean depth (m)	13.1
Max depth (m)	26
Perimeter (km)	58.6
Precipitation (mm/year)	2300
Height (m.a.s.l.)	12
Renovation time (months)	12.5
Trophic degree	Eutrophic
Seasonal stratification	Yes
Main watershed use	Forestry, recreational, tourism, residential and agriculture.
Main lake use	Recreational, Tourism, Receptor
Algal bloom	Yes
Direct tributaries	11
Type of basin	Coastal, dendritic, exhorreic
Alimentation	Pluvial

The Lake Lanalhue Basin, like all Nahuelbutan lake basins, has a pluvial alimentation regime, making precipitation a highly significant factor in the lake's water balance. Lake Lanalhue receives an average annual rainfall of 2300 mm (O. Parra et al., 1999; O. Parra, 2003b; O. Parra et al., 2005a).

The precipitation in the region is heavily influenced by the Nahuelbuta mountain range, which acts as a natural climatic barrier (Bravo Orrego, 2018). Precipitation is partially held back on the western side of the mountains,

causing coastal areas such as Lake Lanalhue to receive more rainfall than the eastern slopes (Bravo Orrego, 2018). As a result, the coastal region where Lake Lanalhue is located is abundant in water resources, evidenced the presence of several rivers, lakes, lagoons, and wetlands (Huenupil-Marihuen. et al., 2010).

In central-Chile (30°S - 41°S), most rainfall originates from cold fronts associated with migratory low-pressure systems embedded in the mid-latitude westerlies (Fuenzalida, 1982). The extents to which these cold fronts penetrate central Chile is influenced by the subtropical anticyclone in the southeastern Pacific (Montecinos & Aceituno, 2003), which responds to the El Niño-Southern Oscillation (ENSO) (Barría et al., 2021; Garreaud et al., 2009). ENSO has a strong influence on both interannual and winter precipitation variability in the region (Quintana & Aceituno, 2012; Rutllant & Fuenzalida, 1991; Valdés-Pineda et al., 2016). Additionally, low-frequency precipitation is modulated by the Pacific Decadal Oscillation (PDO) (Valdés-Pineda et al., 2018). A long-term decline in precipitation correlates with the Antarctic Oscillation (AAO), further linked to broader climatic changes (Quintana & Aceituno, 2012).

In recent years, central Chile has been severely impacted by the Megadrought, which began in 2010 and resulted in a 25% to 45% reduction in precipitation (Garreaud et al., 2020). The region has faced significant climatic strain over the past decade.

This study aims to establish a framework for monitoring Lake Lanalhue's water levels over the last 6-7 decades. Ideally, this monitoring system would capture both climatic and anthropogenic influences. However, the present study focuses on reconstructing the lake's water level response to climatic forcing since 1950, as further discussed in Section 5. .

3. Methodology

This section outlines the methodology, divided into three parts: Section 3.1. summarizes the overall work strategy, Section 3.2. focuses on the data used, and Section 3.3. details the lake water level construction.

3.1. Work strategy

We conduct this research following the workflow outlined in Figure V.2.

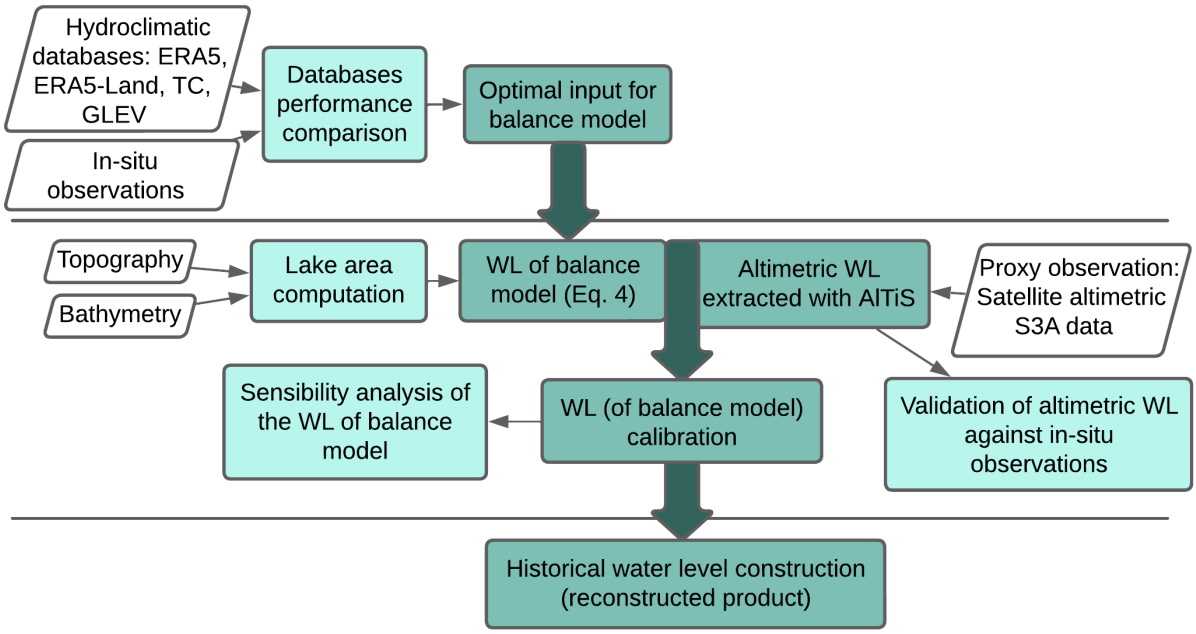


Figure V.2. Workflow for long-term water level (WL) construction.

The process begins with a comparison of the in-situ (Section 3.2.1. and Table V.2) and hydroclimatic (Table V.3) databases, as described in Section 3.3.1. 3.2.2. . Based on this comparison, we select the optimal inputs for the WB model (Eq. 4), as discussed in Section 4.1.2. . Using these inputs, the levels from the WB model (Eq. 4) are constructed for the period 2016-2023, aligned with the availability of Sentinel-3A data (Section 3.2.3.). The required lake area is computed as outlined in Section 3.3.3. .

The levels of the WB model are then calibrated using the satellite altimetric data (proxy observation) from Section 3.2.3. , to avoid using in-situ water level data. Calibration is performed using a linear fit. Once calibrated,

the historical water level is reconstructed using the conceptual hydrological or WB model (Eq. 4) and the climatological lake area from Section 3.3.3. .

In the results section, we provide insights into WL changes driven by climatic forcing. In this analysis we use the climatic indices listed in Table V.2, and Mann-Kendall and Theil-Sen trend estimators to analyze long-term behaviour. Additionally, we conduct a sensibility test described in Section 3.3.5. . The Theil–Sen estimator is a robust method for linear regression that selects the median slope from all pairs of sample points. It is resistant to outliers and is considered the most popular nonparametric technique for estimating linear trends (Tilgenkamp 2025). On the other hand, Mann-Kendall test chooses between the null hypothesis of trend absence against the alternative of trend of a time series. If the result is 1, the null hypothesis is rejected and there is indeed a significant trend at the alpha significance level (usually of 0.05). On the contrary, if the result is 0, it indicates a failure to reject the null hypothesis at the alpha ($\alpha = 0.05$) significance level (Fatichi 2025).

Finally, we conduct a validation of the methodology against in-situ lake water level data in Section 3.3.6. .

3.2. Data

In this study, we construct the long-term water level of Lake Lanalhue using hydroclimatic databases (detailed in Section 3.2.2.), calibrated with the altimetric water level data (described in Section 3.2.3.). Additionally, we incorporate in-situ data on atmospheric and climatological variables, bathymetry and DEM (Section 3.2.1.).

3.2.1. In-situ and others

Several databases are used in the Results (Section 4.) and Discussion (Section 5.), which are detailed in this section and summarized in Table V.2. Lanalhue lake water level records, precipitation, air temperature, river discharge and monthly climate indices (ENSO3.4, PDO, AAO) are employed to compare hydroclimatic databases (Section 4.1.1.), construct the optimal input for the water balance (Section 4.1.2.) and interpret long-term variations in lake levels (Section 4.3.).

Lake water level records come from the Chilean General Directorate of Water (DGA), through transparency law request, for the period 1987-2024. This dataset contains lake volume and water height, and its location can be seen in Figure V.3.

Precipitation data comes from daily in-situ measurements at the Cañete [DGA] (1961-present), Contulmo [DGA] (1987-2019) and Carriel Sur (1950-

present) meteorological stations. Mean daily air temperature is available only from the Carriel Sur station from (1966-present). Both precipitation and air temperature data are sourced from Climatic Explorer CR(2) ((CR)2, 2025), a website that compiles climatic observations for Chile. The in-situ stations are located in the coordinates shown in Table V.2.

Table V.2: Databases available for water level construction. Variables: in-situ (i-s) lake water level height, i-s daily precipitation ((CR)2), i-s air temperature ((CR)2, 2025), river discharge (DGA, 2025a), ASTER GDEM V3 Elevation (Tachikawa et al., 2011), Lake Lanalhue bathymetry (provider: EULA-Chile), and climate indices such as ENSO 3.4 (NOAA, 2024c), PDO (NOAA, 2024d), AAO (KNMI, 2024; NOAA, 2024b) and Global Warming (Haustein et al., 2017). Columns: i) variable, ii) station name and data source, iii) available period, iv) coordinates (latitude (lat), longitude (lon)) in the case of punctual data, data extraction in the case of data over an area and "-" if it does not apply. v) Data frequency, vi) spatial resolution and vii) station elevation (if applicable).

<table>
<tr><th>Variable [unit]</th><th>Station name (source)</th><th>Available period</th><th>Coordinates (lat, lon) or data extraction</th><th>Frequency</th><th>Spatial resolution [m]</th><th>Station elevation (m.a.s.l.)</th></tr>
<tr><td>i-s Lake water height</td><td>LAGO LANALHUE</td><td>1/1/1987 – 31/7/2024</td><td>-37º5’57.84’’; -73º43’0.48’’</td><td>Daily</td><td>-</td><td>12</td></tr>
<tr><td rowspan="4">In-situ precipitation [mm]</td><td>Cañete (DGA, 2025a)</td><td>1/12/1961 - present</td><td>-38º58’53.04’’; -73º46’12.00’’</td><td rowspan="5">Daily</td><td rowspan="6">Punctual data</td><td>78</td></tr>
<tr><td>Contulmo (DGA, 2025a)</td><td>1/6/1987 - 30/9/2019</td><td>-38º58’53.04’’; -73º46’12.00’’</td><td>41</td></tr>
<tr><td rowspan="3">Carriel Sur (DGA, 2025a)</td><td>1/1/1950 - present</td><td rowspan="3">-36º13’14.88’’; -73º56’16.08’’</td><td rowspan="3">12</td></tr>
<tr><td>In-situ air temperature</td><td>1/1/1966 - present</td></tr>
<tr><td>River discharge [m³/s]</td><td>Río Elicura en puente Elicura 08822002-1 (DGA, 2025a)</td><td>15/12/2015 - 1/12/2020</td><td>-37º3’45.72’’; -73º46’50.88’’</td><td>Daily</td><td>25</td></tr>
</table>

ASTER GDEM V3 Elevation [m.a.s.l]	(Tachikawa et al., 2011)	-	Data extraction in Lake Lanalhue basin	-	30	-
Bathymetry of Lake Lanalhue	(provider: EULA-Chile)	Data collected on 22/3/2019	Transects over Lake Lanalhue	-	100	-
ENSO 3.4 index	(NOAA, 2024c)	1/1/1950 - present	-	Monthly	-	-
PDO index	(NOAA, 2024d)	1/1/1900 - 1/12/2021				
AAO index	(KNMI, 2024; NOAA, 2024b)	i) 1/1/1948 - 1/12/2012 (NOAA, 2024b), ii) 1/1/1979 - 1/12/2024 (KNMI, 2024)				
Global Warming Index	(Haustein et al., 2017)	1950 - 2017	-		-	-

Additionally, river discharge comes from daily in-situ measurements at the Río Elicura en puente Elicura 08822002-1 [DGA] station, covering the period from 2015 to 2020, and is extracted from the General Directorate of Waters (DGA) hydrometric network (DGA, 2025a).

ENSO3.4, AAO and PDO indices are obtained from NOAA and KNMI Climate Explorer sites (KNMI, 2024; NOAA, 2024c) covering data from 1950 to the present. El Niño (La Niña) is a phenomenon in the equatorial Pacific Ocean characterized by a five consecutive 3-month running mean of sea surface temperature (NOAA reconstruction) anomalies in the Niño 3.4 region (east-central equatorial Pacific between 5N-5S, 170W-120W) that is

above (below) the threshold of +0.5°C (-0.5°C) (NOAA, 2024c). The ENSO 3.4 index is particularly useful for studying the El Niño phenomenon in South America due to its representation of sea surface temperature anomalies in the central equatorial Pacific. This region directly influences climate patterns in South America, such as changes in precipitation and temperature. While other ENSO indices, like ENSO 1+2 and ENSO 4, are relevant for local conditions, they do not capture as effectively the broader, more impactful variations of El Niño and La Niña that affect South American weather and climate on a larger scale (Merryfield & Lee, 2023; Trenberth & Hoar, 1996; Xu et al., 2025).

PDO is often described as a long-lived El Niño-like pattern of Pacific climate variability (NOAA, 2024d). The PDO index is based on NOAA's extended reconstruction of SSTs (ERSST). It is constructed by regressing the ERSST anomalies against the Mantua PDO index (Mantua, 1 for their overlap period, to compute a PDO regression map for the North Pacific ERSST anomalies. The ERSST anomalies are then projected onto that map to compute the PDO index (NOAA, 2024d). As there is no AAO data available for the whole period studied (1950-2022), we combined two datasets (KNMI, 2024 and NOAA, 2024a). The AAO index is constructed by projecting the daily (00Z) 700mb height anomalies poleward of 20°S onto the leading mode of Empirical Orthogonal Function (EOF) analysis of monthly mean 700 hPa height during 1979-2000 period (NOAA, 2024b). We used the NOAA AAO index until 2012, and for 2012 onwards, we used the KNMI AAO index.

Besides the climatic indices, we have added a Global Warming Index (Haustein et al., 2017). It estimates anthropogenic warming and separates anthropogenic and natural forcing in the calculation and results.

In addition, ASTER GDEM V3 (Tachikawa et al., 2011) and the bathymetry of Lake Lanalhue are utilized to construct water levels (Section 4.1.2.) through the lake area in the water balance model (Section 3.3.4.). The bathymetric data, provided by EULA-Chile, originally consisted of transects across the lake with depth measurements, which were interpolated into a 100-meter spatial resolution grid.

3.2.2. Hydroclimatic databases

In this section, we present the hydroclimatic databases used to identify the best combination of variables for the water balance equation (Eq. 4): ERA5, ERA5-Land, TerraClimate and GLEV. The rationale for selecting these databases is also explained. Table V.3 summarizes the key details of these databases and Table V.4 provides a comparison of how the input variables for the water balance are computed.

Reanalysis datasets provide more than just precipitation data; they include variables such as temperature, relative humidity, evaporation, which makes them more useful for hydrological studies compared to interpolated datasets. Reanalysis products like ERA5 and ERA5-Land are generated from both models and observations, incorporating data from satellites and in-situ

sources. With improved data assimilation systems and higher spatiotemporal resolution, extending back to the 1950s, these datasets outperform earlier versions of ERA5 and other reanalysis products (X. Fang & An, 2022; Jiang et al., 2021; Taghizadeh et al., 2021).

i) ERA5 Monthly Aggregates (ECMWF/C3S, 2024a): ERA5 is a global reanalysis dataset with a spatial resolution of 27.83 km. It provides monthly accumulated values for precipitation, evaporation, runoff and other climatic variables. Reanalysis combines model data with observations from around the world, using physical principles to create a comprehensive dataset. ERA5 relies on an atmospheric model coupled with a land-surface model (HTESSEL) (ECMWF, 2020). However, for this study, we will only use precipitation data from ERA5, as it is the most critical variable for comparison with ERA5-Land.

ii) ERA5-Land Monthly Aggregated (ECMWF/C3S, 2024b): ERA5-Land is a global dataset with an enhanced spatial resolution of 9 km compared to ERA5. It is produced by replaying the land component of the ERA5 climate reanalysis, using ERA5 atmospheric variables as forcing, which already include observational data. ERA5-Land provides precipitation, total evaporation, and separated evaporation (i.e., evaporation from bare soil, transpiration and interception), as well as runoff and other climatic variables. This dataset is available on the GEE platform (ECMWF/C3S, 2024b).

iii) TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces (Abatzoglou et al., 2018): TerraClimate is a high-resolution reanalysis dataset with a spatial resolution of 4 km (Abubakar, 2024; UCM, 2024). It is based on interpolated time-varying anomalies from CRU Ts4.0/JRA55 and the high-resolution 1-km gridded climatology from WorldClim (Abatzoglou et al., 2018; Fick & Hijmans, 2017). This combination gives TerraClimate both a stationary cycle and interannual variability based on real interpolated data (WorldClim and CRU). TerraClimate also produces monthly surface water balance datasets, which include hydrological useful variables such as reference evapotranspiration, precipitation, temperature, and plant extractable soil water capacity. It is available on GEE (UCM, 2024). These advantages made TerraClimate a key comparison dataset for ERA5 products.

iv) Global Lake Evaporation Volume (GLEV) dataset (G. Zhao et al., 2022): GLEV provides the highest temporal resolution dataset for lake surface area and evaporation, covering 1.4 million lakes worldwide (Woolway et al., 2024). Given our focus on medium and small-sized lakes, GLEV was chosen for this study. The dataset includes monthly evaporation and varying lake areas. GLEV reports evaporation as volume ($10^6 m^3$/month), which we converted to millimeters of evaporation using the lake area data ($area$) provided by GLEV.

Table V.3. Hydroclimatic databases selected to provide input for the water balance equation (Eq. (4)) for Lake Lanalhue: i) ERA5 (ECMWF/C3Sa), ii) ERA5 Land (ECMWF/C3Sb) iii) TerraClimate (UCM, Abatzoglou et al. 2018) and iv) Global Lake Evaporation Volume (GLEV, Gang Zhao 2021).

Database	Variables [unit]	Available period	Spatial resolution [km]	Frequency available
ERA5	Precipitation [m]	1/1/1979 - 1/6/2020	31	Daily, Monthly
ERA5-Land	Precipitation, evaporation and runoff [m]	1/2/1950 - present	9	Hourly, Daily, Monthly
Terra Climate		1/1/1958 - 1/12/2023	~4	Monthly
GLEV	Evaporation volume [$10^6 m^3$/month] and lake area [km^2]	1/1985 - 12/2018	It does not apply since it is over the whole lake	

Table V.4. Comparison of the computation of key variables within the hydroclimatic databases (ERA5, ERA5-Land, TerraClimate and GLEV) that can be used as input for the water balance equation (Eq. 4): precipitation (P), evaporation (E) and runoff-and-storage (R+ΔS). For ERA5, only precipitation will be used for comparison, as it is the most critical variable in this study; therefore, evaporation and runoff-and-storage are not reviewed. Since GLEV is solely an evaporation dataset, the other variables do not apply.

Database	Variable		
	Precipitation (P)	**Evaporation** (E)	**Runoff and storage** (R+ΔS)
ERA5	Precipitation monthly sum (ECMWF/C3Sa).		
ERA5-Land	As the precipitation falls, it is retained in an interception layer, until saturated. Then it is transformed into runoff.	Evaporation is divided into interception, evaporation over the basin (as evaporation of bare soil and transpiration of vegetation) and evaporation over the water. As precipitation falls, it is retained as interception until saturation. After that it is transformed into runoff. All evaporation (excluding interception) acts over the	The runoff is separated into the surface runoff and the subsurface runoff, which we consider the storage term. The subsurface fluxes are determined using a soil-water equation (Balsamo et al., 2009).

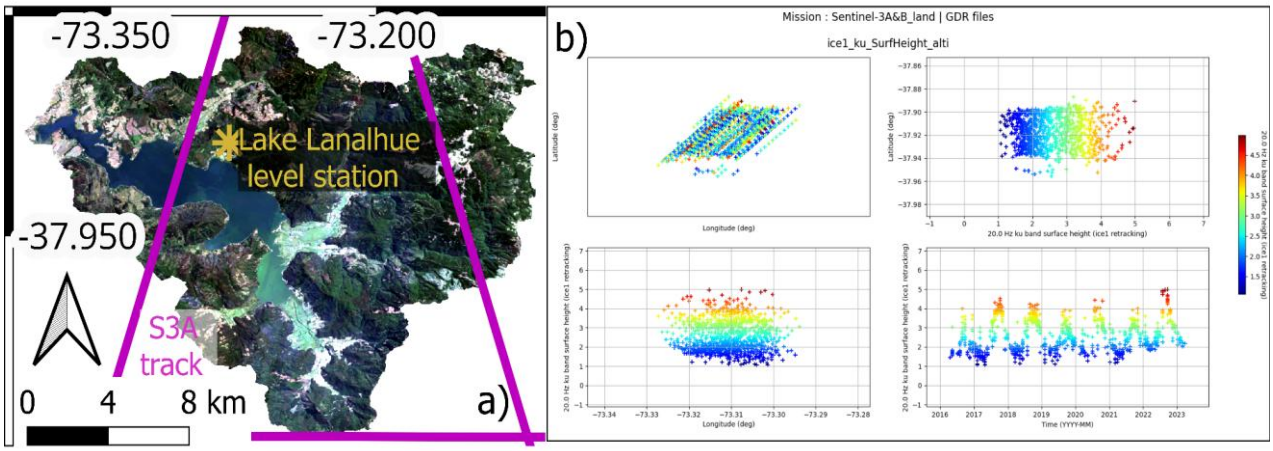
		runoff. Evaporation in ERA5-L uses the ERA5 computation of evaporation, which is based on surface energy balance calculations with the vegetation parameters set to "crops/mixed farming" and assuming "no stress from soil moisture" (Muñoz-Sabater et al., 2021).	The interception layer has already been discounted for this term.
Terra Climate	In this case, precipitation transforms into runoff (Abatzoglou et al., 2018).	Evaporation acts over runoff. It is calculated using the Penman Montieth approach (Abatzoglou et al., 2018).	Runoff was derived using a one-dimensional soil water balance model. In this model, runoff is considered as the excess of liquid water supply (precipitation and snowmelt) used by monthly evaporation and soil moisture recharge (Abatzoglou et al., 2018).
GLEV	-	Calculated using an algorithm based on the Penman combination equation but explicitly quantifying the heat storage changes. For each lake, the forcing data were averaged over the lake surface area from the three meteorological forcing datasets (TerraClimate, ERA5, and GLDAS) (G. Zhao et al., 2022).	-

3.2.3. Satellite altimetric data

The only Nadir altimetry theoretical groundtrack that overpasses the study area is S3A (ESA), pass 220. S3A is composed by three instruments: the dual-frequency radar altimeter (SRAL), a microwave radiometer (MWR) that supports the SRAL by providing wet atmosphere correction, and a precise

orbit determination package for determining the position (ESA). It crosses the study area over Lake Lanalhue (see Figure V.3) and will thus provide lake water level between 16/04/2016 and today with a sampling interval of 27 days. The used period is until 13/04/2023. Since our intent is to have long time series of WL, we did not consider in this study data from SWOT swaths, that would have provided WL only from mid-2023. Data details are presented in Figure V.3.

Figure V.3. a) Track of S3A over the Lake Lanalhue composite, and b) its visualization in the AITiS software (version 2.2.8).



Satellite radar altimetry is a technique, which allows retrieving WL from the difference between the satellite's altitude and the range from the on-board instrument to the water surface. Appropriate atmospheric and geophysical corrections (e.g.: radar signal propagation delays, tides) are applied to this

difference, allowing the calculation of long-term time series of average WL with revisit periods depending on the satellite's repeat cycle.

To extract this data, we use the Altimetry Time Series (AlTiS) Software (CTOH, 2024), developed by the Centre de Topographie des Océans et de l'Hydrosphère (CTOH) as part of its National Observation Service activities. AlTiS is an analysis tool designed to process geophysical data records (GRD) of altimetry missions over small areas, such as rivers, lakes and floodplains, to create water level (WL) time series (CTOH, 2024). This free software can be downloaded from CTOH (2024). Using the AlTiS software, the Level 2 Geophysical Data Records (L2 GDR) are processed manually, allowing for the selection and removal of individual measurements based on a visual inspection of their distribution over the lake. Other ranking methods, such as peakiness and sigma0 ($\sigma 0$), are also applied depending on the water body's characteristics. This approach ensures highly accurate measurement processing but requires manual intervention, making it less suitable for large-scale calculations across multiple lakes. However, it is particularly effective for small lakes, making it well-suited to our case study.

Our processing generated a time series (TS) of lake water WL from April 16, 2016, to April 13, 2023, comprising 91 daily water level measurements with a standard deviation of 74.03 cm. The original 27-day frequency data was interpolated to a monthly frequency to match the time resolution of the water

balance (WB) inputs and reduce uncertainties. The extracted WL data for Lake Lanalhue, processed using AlTiS, is shown in Figure V.3a.

3.3. Water balance construction

The water balance construction process is carried out in four steps: i) data comparison (Section 3.3.1.), ii) input construction based on the optimal combination of variables resulting from (i) (Section 3.3.2.), iii) lake area calculation (Section 3.3.3.) and iv) water balance construction (Section 3.3.4.). Additionally, a sensibility analysis (Section 3.3.5.) and validation of altimetric and WB levels against in-situ lake levels (Section 3.3.6.) are carried out.

3.3.1. Data performance comparison

In this section, we compare the different databases available for Lake Lanalhue (in-situ from Table V.2, and hydroclimatic data from Table V.3) that are used to construct the water balance equation (Eq. 4).

The comparison involves building the climatology of all variables affecting the water balance model (Eq. 4), including precipitation, evaporation over the lake and basin and runoff-and-storage (results shown in Figure V.4). We assess the performance of the hydroclimatic databases by comparing their climatologies with in-situ data from the *Contulmo* and *Cañete [DGA]* stations

(see Table V.2). This comparison is done using several statistics measures: mean (μ) and standard deviation (σ), correlation coefficient (*R*), square of the correlation coefficient (R^2), root-mean-square error (*RMSE*) and *Bias.* Note that, in this comparison, as we include in-situ precipitation data, the comparison for this variable is carried out around the two in-situ stations: Cañete and Contulmo [DGA] stations. Their equations are shown as follows.

$$R = \left(\frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \right) \qquad (1)$$

$$NRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad (2)$$

$$bias = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i) \qquad (3)$$

, where x_i and y_i are the ith observations of datasets x and y, $\underline{x}$ and $\underline{y}$ are their mean values and n is the number of observations.

According to Willmott (1981) and Ji et al., (2015), $bias$ represents the average difference, $RMSE$ indicates the overall difference between two datasets, R measures linear correlation between two sets of data, and R^2 represents the proportion of shared variance.

$bias$ does not take in account the predictive precision of the time series as it focuses on the average. $RMSE$ is related to precision as it belongs to the family of measures of the fit regarding the distance of the regressor to the training points. Although it has been widely used, it has interpretability limitations. As it depends heavily in the variable ranges, the RMSE values are not directly comparable. In this case, RSME was computed using the entire time series fitted by a first-degree polynomial regression (Chicco et al., 2021). Correlation coefficient, R, accounts for both precision and bias, although it does not inform the individual contribution of each one (Wadoux & Minasny, 2024). Finally, R^2 is the most widely applied measure, but it does not quantify $bias$, and can be low for an accurate and high for an imperfect model, respectively (Onyutha, 2021).

The results of this analysis are presented in Section 4.1.1. .

3.3.2. Input construction

After comparing the variables from in-situ and hydroclimatic databases, we will select the optimal dataset to construct the input for the water balance equation (Eq. 4). We opted to use ERA5-L for the water balance (WB) model due to its robust data assimilation system, which provides multiple variables crucial for hydrological studies. It also offers enhanced spatial resolution compared to earlier ERA5 products and covers a long temporal range starting from 1940. Besides, ERA5-Land has been used to force lake hydrodynamic

models in small lakes as Lake Lanalhue (Bongioannini Cerlini et al., 2022; Saraceni et al., 2025).

However, improvements will be made to both the WB model and its inputs. Amplitudes will be adjusted using linear fits based on altimetric water level (WL) data and Global Lake Evaporation Volume (GLEV) evaporation, which is more refined than other dataset estimates. Additionally, delays in evaporation and runoff-and-storage terms, which are influenced by temperature and precipitation changes, will be corrected. These corrections will be based on in-situ runoff data, represented by river discharge measurements from the region. The delays will be determined by identifying the time shift that maximizes Pearson's correlation between the datasets. The details of these improvements are written as follows.

i) Precipitation (P in Eq. 4) over the lake is derived from ERA5-L but adjusted using the long-term linear trend averaged from ERA5 and TC.

ii) Evaporation over the lake (E_L in Eq. 4) is delayed by approximately 1.4 months according to GLEV (see Section 3.2.2.), providing an improvement over the ERA5-L and TC evaporation estimates. This indicates that GLEV evaporation occurs 1.4 months later than in ERA5-L.

iii) Runoff and storage ($R + \Delta S$ in Eq. 4) represent the water flow entering the lake, which is the precipitation remaining after saturation of the interception layer and subsequent evapotranspiration in the basin. As this term

is due to precipitation, this term was also corrected using the long-term trend from (i). Additionally, the runoff-and-storage series is delayed by 0.25 months compared to in-situ runoff, as represented by the river discharge data (Table V.2), and described in Section 3.2.2. .

iv) Basin evapotranspiration (transpiration from vegetation and evaporation from base soil, excluding the interception layer, which is already removed in the $R + \Delta S$ calculation) is delayed by 1.4 months according to GLEV (see Section 3.2.2. , assuming similar behaviour for both lake and basin evaporation.

3.3.3. Lake area calculation

To calculate the water balance using Equation 4, we must convert the hydroclimatic variables from vertical meters or rate changes into water volumes. This requires the lake areas, which represent water gains or losses (G. Zhao et al., 2022).

To generate a historical lake area series, we combined the SRTM topography (Tachikawa et al., 2011) with the bathymetry of Lake Lanalhue (Table V.2). We assumed that the zero level of the bathymetry corresponds to the collection date (March 22, 2019, according to Table V.2). The altimeter height was adjusted to zero as the reference level for this time series. From there, height isolines were built over the merged bathymetry-topography to

calculate the lake area at each altimeter reading. This process provided the lake area for the period covered by the altimeter data (16/4/2016 - 13/04/2023).

To extend the lake area calculation into the past without using in-situ water level data, we generated a climatology for the lake area based on the altimeter data period. This climatology was then repeated for each year in the historical record. Lake volume changes were calculated using the relationship between lake level and area. For each altimeter reading, the corresponding lake area was determined from the bathymetry-topography model. Volume change between two points was then estimated as the product of the average lake area and the water level difference, assuming a gradual change in surface area with water level. This may lead to uncertainties depending on the representativity of the climatology in every annual cycle.

3.3.4. Water balance model

The water level in a lake is primarily influenced by four variables: precipitation (rain and snow), evaporation (both from the lake and the basin, including interception and transpiration), runoff (from land and watercourses) and groundwater storage (Bengtsson, 2012; Winter, 1981).

To construct the water balance, we use a standard conceptual model that hat accounts for water gains and losses in the lake (Bengtsson, 2012; Mason et al., 1994). The model is adapted to fit the specific characteristics of Lake Lanalhue and the available datasets.

Precipitation is the primary water source for the Lake Lanalhue basin. Water enters the lake directly through precipitation or indirectly via delayed runoff and groundwater storage from the surrounding basin. Direct precipitation is the only water gain over the lake, while evaporation is the only loss. The first term of the water balance (Eq. 4) represents precipitation (P_L) minus evaporation over the lake (E_L), and this is multiplied by lake area to calculate volume changes.

In the basin, runoff-and-storage ($(R + \Delta S)_C$) represent the transformed precipitation that flows into the lake as surface runoff and groundwater storage. Based on the formulation of hydroclimatic databases (Table V.4), we assume that all lake inflows are accounted for within the runoff-and-storage term.

The only outflow from the lake is the 'Estero Puyehue,' a small and slow-moving watercourse. As defined by the Geographic Terms Glossary of Chile, an 'Estero' is a small river or stream (BCN, 2024). Given the Estero's minimal and intermittent flow, outflows were excluded from the current analysis. However, while measuring discharge with a flowmeter in the future would improve the model's accuracy, the insignificant flow of the Estero is unlikely to affect the overall results of this study.

Runoff is affected by soil evaporation, watercourse evaporation and vegetation evapotranspiration (E_C), which are included as losses in the basin. The second term of the water balance (Eq. 4) represents these gains and

losses in the basin, and it is multiplied by the basin area (A_C) minus lake area: $A_C - A_L$., while (ΔV) represent volume changes.

$$\Delta V = (P_L - E_L)A_L + ((R + \Delta S)_C - E_C)(A_C - A_L) \qquad (4)$$

3.3.5. Sensibility analysis

A sensibility test will be conducted to evaluate the model's response (Eq. 4) to different inputs. The model will first be run climatological averages for all inputs as a control, represented by a constant line over the 12 months. Next, we will assess the individual effect of precipitation (P_L and $(R + \Delta S)_C$) and evaporation (E_L and E_C). First, precipitation-related inputs will be varied following the climatology, while keeping other inputs as a mean value, and then evaporation inputs will be varied in the same manner. Finally, the climatology will be adjusted by replacing the amplitude with one or two standard deviations, and the resulting percentage change from the control will be used to determine which variable has the greatest impact and by how much.

3.3.6. Validation of altimetric and WB levels against in-situ WL

Up to here, we have not used in-situ lake water height (Table V.2). We use it in this section to check the performance and validate the altimetric data first, and secondly, the generated lake level model based on WB (Eq. 4). We will show the results graphically, and we will add statistical metrics to analyze

their differences. Also, we will compare delays among time series to analyze their seasonal timing.

4. Results

4.1. Water balance construction

4.1.1. Data performance comparison

This section compares the available databases for Lake Lanalhue (in-situ and hydroclimatic). As described in section 3.3.1. , we constructed climatologies for all variables that affect the water balance: a) precipitation, b) lake evaporation, c) basin evaporation, and d) basin runoff-and-storage. The results are shown graphically in Figure V.4.

Figure V.4. Climatology of the hydroclimatic variables from the datasets used to build the water balance (Eq. (4)) over different time periods. Datasets: ERA5, ERA5-Land, TerraClimate, Global Lake Evaporation Volume (GLEV). Variables: a) precipitation in the Lanalhue basin (P). b) Evaporation over the lake (E_{lake}). c) Evaporation in the basin (including transpiration and evaporation, excluding interception) (E_{basin}). d) Runoff and Storage in the basin (including surface and subsurface runoff) ($R + \Delta S$).

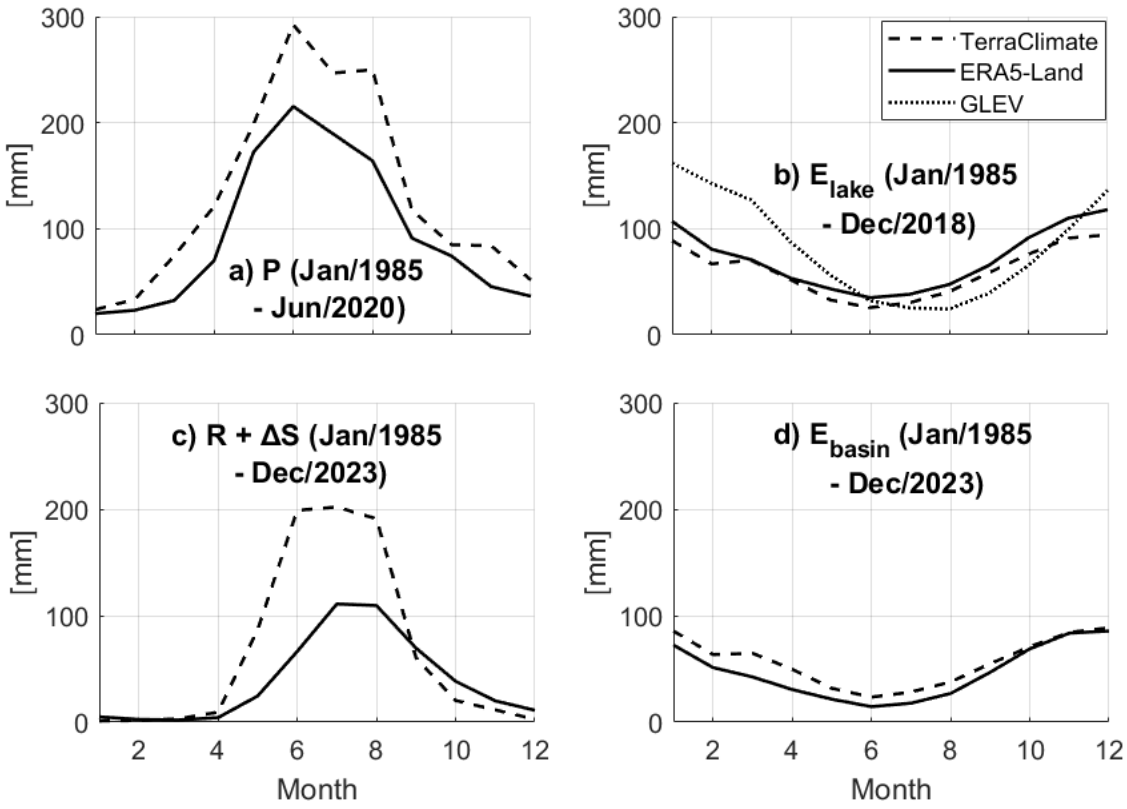


Figure V.4 highlights the seasonal variability of the water balance inputs. Precipitation peaks in June, marking the start of winter in the Southern Hemisphere, but in the ERA5-L dataset, it is transformed into runoff-and-storage with a one-month delay. During the winter months (June, July, and August) both lake and basin evaporation reach their lowest values.

In comparing the databases (Figure V.4), we observe that they show similar amplitudes except for runoff and storage ($R + \Delta S$) in Figure V.4c. The difference between TerraClimate (TC) and ERA5-Land (ERA5-L), can be

attributed to how ($R + \Delta S$) is formulated in each model (see Table V.5). In ERA5-Land, the evaporation component includes an interception layer that must become fully saturated before water contributes to runoff-and-storage, whereas TC does not explicitly include this interception layer. Consequently, ERA5-L shows greater water loss from precipitation to runoff and storage compared to TC. Additionally, part of the amplitude difference is due to the higher precipitation estimates in TC (Figure V.4a) which is reflected in its $R + \Delta S$ values.

Regarding delays among the databases, we observe differences in their representation of evaporation over the lake and runoff and storage. First, the differences between in ($R + \Delta S$) between TC and ERA5-L can be explained by the distinct hydrological models used. In TC, runoff and storage are combined into one term, where precipitation is transformed into surface runoff and subsurface storage. In contrast, ERA5-L separates these processes: part of the precipitation is immediately converted into surface runoff (R), while another portion gradually becomes subsurface runoff (ΔS) with a 1-to-2-month delay in the study area. Second, the difference in evaporation estimates between GLEV and ERA5-L/TC are likely due to the improvements in GLEV's evaporation computation, which explicitly accounts for heat storage changes in the Penman equation (Zhao et al. 2022; see Table V.4).

We also calculated statistical measures for the hydroclimatic databases, including the mean (μ) and standard deviation (σ), shown in Table

V.5. Additionally, we computed i) the square of the correlation coefficient (R^2), ii) root-mean-square error (*RMSE*), iii) bias and iv) correlation coefficient (R). The results can be seen in Table V.5, based on Equations 2 to 4. Note that, in this comparison, we include in-situ precipitation data. This is why, for this variable, the comparison is carried out around the two in-situ stations: Cañete (left side) and Contulmo [DGA] (right side) stations. For this comparison, in-situ were not spatially interpolated. Instead, the comparison has been done punctually in each in-situ station.

Table V.5. Mean (μ) and standard deviation (σ) of monthly hydroclimatic databases used to build the water balance (Eq. 4) for ERA5, ERA5-L, TC and GLEV. Periods are in the third column. For precipitation (P, second row), values are calculated at two stations: Cañete (left side) and Contulmo [DGA] (right side) stations, resulting in two values for μ and σ. Lake evaporation, E_{lake}, refers to over the lake, while basin evaporation (E_{basin}) and runoff and storage ($R + \Delta S$) are time series averaged across the Lanalhue basin.

Variable	**Time Serie**		**Period**	**μ [mm]**		**σ [mm]**	
P	In-situ	Cañete and Contulmo [DGA] stations	Cañete [DGA]: 1/12/1979 - 1/6/2020 Contulmo [DGA] 1/6/1994 - 30/9/2019	98.77	111.25	100.64	113.00
	ERA5			105.60	95.65	102.62	89.39
	ERA5-L			98.29	91.13	94.36	84.77
	TC			132.53	128.25	122.19	115.54
E_{lake}	GLEV		1/1985 - 12/2018	83.05		48.25	
	ERA5-L			71.42		29.26	
	TC			60.56		25.24	
E_{basin}	TC		1/1958 - 12/2022	57.29		24.63	
	ERA5-L			45.59		25.38	
$R + \Delta S$	ERA5-L			34.82		50.95	
	TC			64.73		102.67	

Table V.6. Comparison of available hydroclimatic data (ERA5, ERA5-Land (ERA5-L), TerraClimate (TC) and GLEV) using the following statistics: i) square of the correlation coefficient (R^2), ii) root mean square error ($RMSE$), iii) bias and iv) correlation coefficient (R). For precipitation (P) calculation is done at two points: Cañete and Contulmo [DGA] stations, resulting in two values resulting in two values for μ and σ. Lake evaporation (E_{lake}), refers to evaporation over the lake, while basin evaporation (E_{basin}) and runoff and storage ($R + \Delta S$) are time series averaged across the Lanalhue basin.

Variable	**Time series**		**Comparison period**	R^2		$RMSE$		$bias$		R	
P	ERA5	In-situ (Cañete and Contulmo [DGA] stations	6/1994 - 9/2019	0.92	0.82	28.19	51.94	-2.79	17.49	0.96	0.91
	ERA5-L			0.93	0.83	27.76	54.88	4.91	22.15	0.96	0.91
	TC			0.92	0.83	49.02	51.06	-30.82	-16.20	0.96	0.92
E_{lake}	ERA5-L	GLEV	1/1985 - 12/2018	0.51		35.96		11.63		0.72	
	TC			0.50		41.84		22.48		0.71	
E_{basin}	ERA5-L	TC	1/1958 - 12/2022	0.78		16.92		11.70		0.88	
$R + \Delta S$	ERA5-L	TC		0.53		82.14		32.26		0.73	

Precipitation is the only source of water in this basin (due to its rainwater-fed nature), making its accurate estimation essential. As shown in Section 4.2. , precipitation drives the seasonal variation in lake WL. For this reason, we included in-situ precipitation data in Table V.5 y Table V.6, extracting hydroclimatic precipitation from the *Cañete* and *Contulmo [DGA]* stations. The results indicate consistency across the three databases.

However, while GLEV evaporation performs similarly to ERA5-L and TC, delay in GLEV affects the statistical results.

While we have examined the short-term performance, it is equally important to assess long-term trends to accurately reflect WL variations, primarily driven by precipitation. For this reason, we present the long-term linear trends as slopes in Table V.7.

Table V.7. Precipitation long-term trends, shown as slopes [mm/month], for in-situ stations Carriel Sur and Cañete [DGA] (stations details in Table V.2). Hydroclimatic databases from ERA5, ERA5-L and TC were extracted from the Google Earth Engine (GEE) near the in-situ stations.

Station	Database	Slope [mm/month]
Carriel Sur	in-situ	-0.567
	ERA5	-0.569
	ERA5-L	0.016
	TC	-0.233
Cañete [DGA]	in-situ	-0.372
	ERA5	-0.612
	ERA5-L	0.083
	TC	-0.299

Table V.7 shows that the slopes are negative in both in-situ stations, indicating a long-term decrease in precipitation, which aligns with known climate change patterns in the area. While TC also reflects a negative trend, ERA5-L shows a positive trend, which does not accurately capture this decline. However, ERA5-L can be adjusted by averaging its trend with those of ERA5

and TC to better represent long-term trends of precipitation in the region. In this case study, it is worth improving ERA5-L, as detailed in Section 4.1.2. .

4.1.2. Input construction

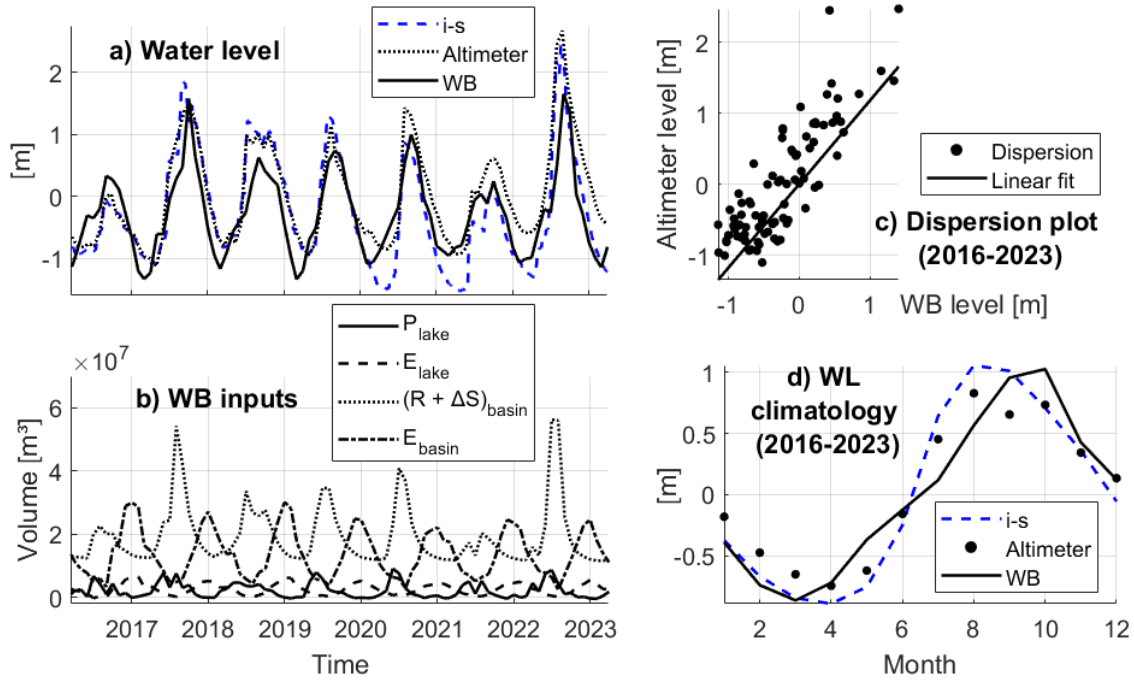
Based on the data comparison in Section 4.1.1. we decided not to use TerraClimate products because their runoff-and-storage term includes both runoff, storage and precipitation, altogether. Since these components are not provided separately, thus the WB equation (Eq. 4) cannot be directly applied, preventing analysis of the temporal delay among them. Instead, we selected ERA5-L due to its superior spatial resolution, which is crucial for small lakes. However, ERA-L requires correction to account for long-term trends. Importantly, it offers continuous data up to the present, making it suitable for future monitoring.

The lake area (A_L in Eq. 4) was determined following the procedure outlined in Section 3.3.3. . The basin area used is 327.43 km² (Table V.1). These inputs were used in Eq. 4 to reconstruct the long-term WL of Lake Lanalhue.

4.2. Water level calibration

In this section, we calibrate and apply a delay to the WL of Lake Lanalhue derived from the WB model (Section 4.1. , from now on referred as WB level) relative to the satellite altimetric WL (Section 3.2.3.). The results are presented in Figure V.5a.

Figure V.5. a) Comparison of in-situ, daily altimetric at one-month time sampling and monthly WB lake levels. WB levels were calibrated through a linear fit and delayed by one-month relative to altimeter levels. b) Monthly precipitation (P_{lake}), lake evaporation (E_{lake}), basin runoff and storage ($(R + \Delta S)_{basin}$), and basin evaporation (E_{basin}). Period: 16/4/2016 - 13/04/2023, according to Sentinel-3A availability (see Section 3.2.3.). c) Dispersion plot of altimeter and non-calibrated delayed WB levels in Lake Lanalhue. d) WL climatology in the period 2013-2016 of in-situ, altimeter and calibrated and delayed WB levels.



In Figure V.5a, we applied a linear fit to calibrate the water balance (WB) level and delayed it by approximately one month relative to the altimetric level, considering that the altimeter accurately represents the actual lake levels, as

shown in Section 4.4. . This suggests that precipitation and runoff-and-storage peak occur first, followed by lake level changes about a month later. Additionally, the reference or mean differences among in-situ, altimeter and WB water levels were eliminated setting the three reference levels to zero. This difference lacks a physical explanation and arises from how the reference level is set in each database.

The altimetric and WB lake levels show a high similarity, as evidenced by the following statistics: R^2 = 0.71, s = 80 (Spearman correlation), and *NRMSE* = 0.11. The relation between altimetric and WB levels will be compared against in-situ levels in Section 4.4. . In environmental variables, 0.81 < R < 1 indicates a very good agreement, 0.61 < R < 0.80 good agreement, and 0.41 < R < 0.60 moderate agreement, 0.21 < R < 0.40 a fair agreement and < 0.2 represents poor agreement) (Altman, 1990). For the spearman correlation, s higher than 0.5 represents a meaningful correlation (Mukaka, 2012). In the case of *NRMSE*, an acceptable range is between 0 and 20% (Maniruzzaman et al., 2015b).

Figure V.5 illustrates a clear seasonal dynamic in the WB and its inputs, with the highest inflows from precipitation (and runoff-and-storage) during winter and the highest outflows from evaporation during summer.

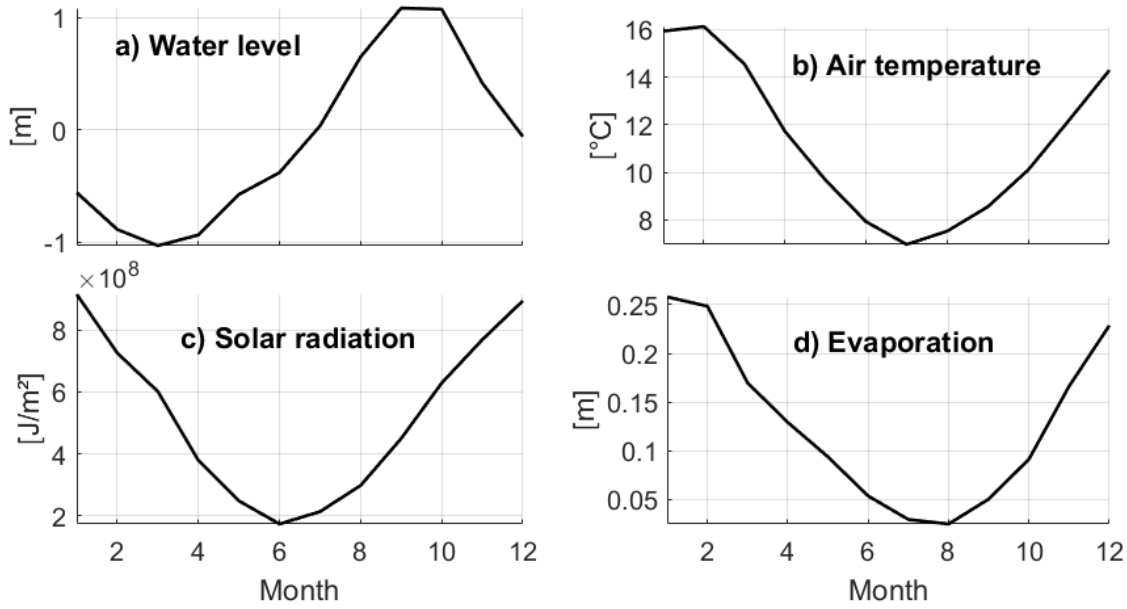
When separating inputs into two categories: precipitation (P , $R + \Delta S$) and evaporation (E_L, E_C), we observe that precipitation drives the seasonal

variation of the WL since it is more critical than evaporation. This is demonstrated by the coefficient of determination R^2, which is 0.86 between precipitation and WL, compared to 0.67 between evaporation and WL. Sensibility test, as described in Section 3.3.5. , further support this: the model responds with a 126.53% change for one standard deviation (std) variation in precipitation, and 316.08% for a two-std variation. In contrast, the model reacts with only 19.22% and 34.08% change for a one-std and two-std variation in evaporation, respectively. These results emphasize the dominant role of precipitation in regulating WL, compared to evaporation.

4.3. Long-term WL reconstruction and climatology

Using the corrections from Section 4.1.2. , from the WB model, we reconstructed the long-term WL of Lake Lanalhue from 1950 to 2022. From that dataset, we derived the climatology of the WL, illustrated in Figure V.6a, which shows typical seasonal variations. The WL peaks in August and September, marking the end of winter, and reaches its lowest levels from February to March, at the end of summer.

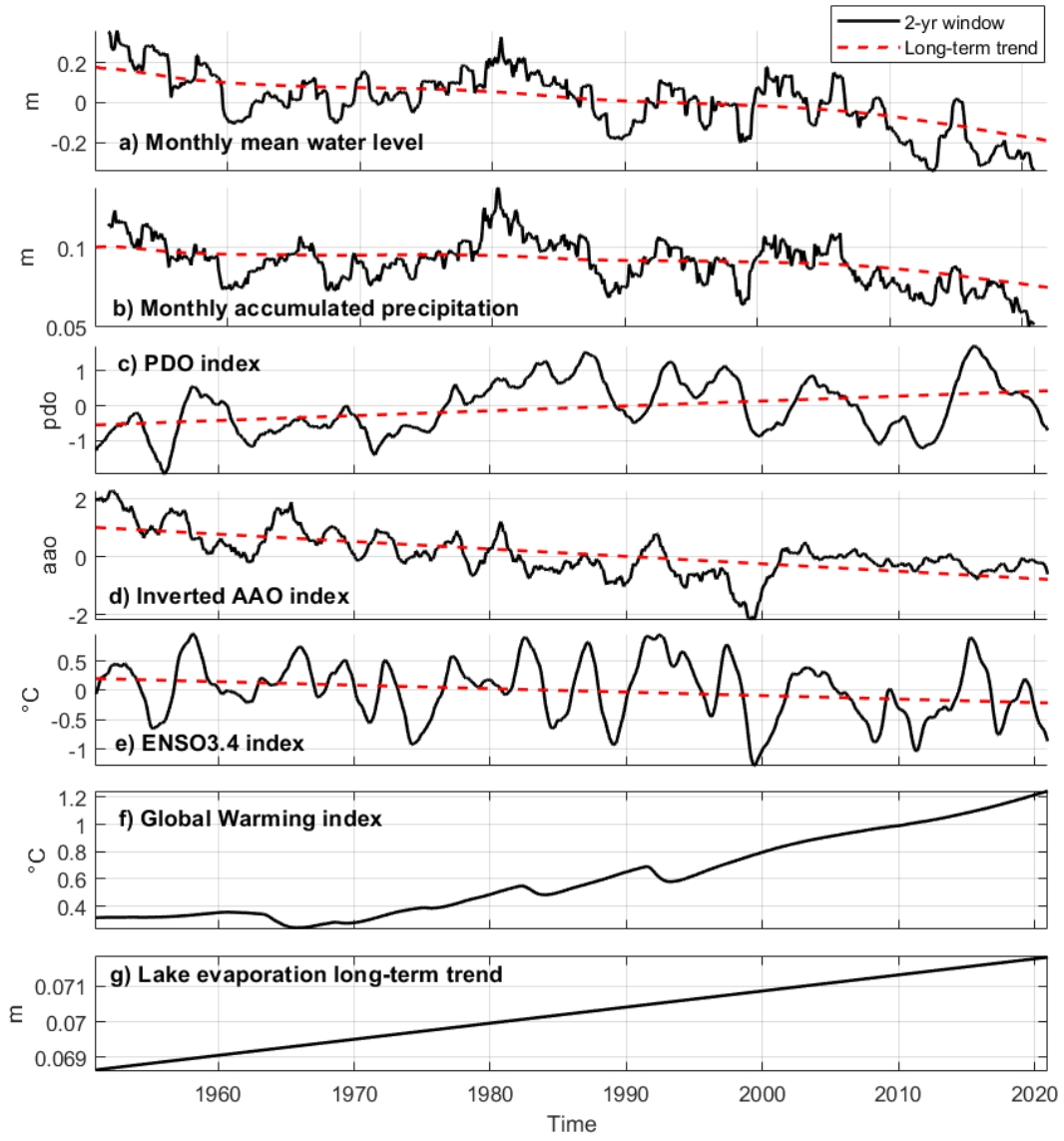
Figure V.6. Climatologies for the period 1950-2022 of: a) Final Lake Lanalhue WL derived using the study's methodology. ERA5-L b) monthly 2-meter air temperature from ERA5-Land, c) monthly solar radiation reaching the surface, and d) monthly lake evaporation.



The peak in WL during September (Figure V.6a) is primarily driven by precipitation, which peaks in June and transforms into runoff entering the lake by July (with a one-month lag). This peak coincides with reduced solar radiation (Figure V.6c), lower air temperature (Figure V.6b) and a minimal evaporation in August (Figure V.6d). Conversely, the lowest WL occurs in March, after the peak air temperatures in January and February (Figure V.6b), and the peak in solar radiation at the end of December or early January (Figure V.6c), and maximum evaporation in January (Figure V.6d).

In addition to the seasonal variability, which was the primary focus of this study, we also present long-term series for precipitation, air temperature, evaporation and climate indices (Global Warming, PDO, AAO, and ENSO3.4) in Figure V.7.

Figure V.7. Time series from 1950 to 2022, showing: 2-year (2-yr) window and long-term a) monthly i-s and retrieved (from WB Eq. (4)) lake water level, b) monthly accumulated precipitation from ERA5-L corrected with the long-term trend of ERA5 and TC (Section 4.1.2.). c) PDO, d) inverted AAO, and e) ENSO3.4 indices. Additionally, f) Global Warming index and g) long-term trend in linear lake evaporation are shown without 2-year window analysis.



As seen in Section 4.2. , runoff-and-storage (driven by precipitation) are the primary modulators of seasonal WL variations, making precipitation the most critical term in the WB. From a long-term perspective, precipitation also

drives long-term trends in the WB (Figure V.7a-b), both showing a declining trend. The relation in the precipitation and WB level trends is given by a Theil-Sen trend estimator of 18,6 mm, indicating a positive relation between both long-term linear trends. Besides, The Mann-Kendall values for precipitation and WB levels at 0.05 confidence level are both 1, indicating that there is indeed a significant trend at a 0.05 confidence level, as explained in Section 3.1. .

This trend is heavily influenced by climate change, which has intensified since 1950 (Figure V.7f) (Burić & Penjišević, 2023). Rising local air temperatures (Figure V.7g) increase evaporation, while declining precipitation (Figure V.7b) further lowers WL. The central-Chile Megadrought, which began in 2010, is also evident in Figure V.7b and has clearly affected the WL (Figure V.7a).

Given that precipitation exerts a stronger influence on lake WL than evaporation (see Section 2.), an exploratory analysis was conducted to investigate the climatic oscillations governing precipitation and, consequently, WL. As shown in Figure V.7, low-frequency variability in precipitation is strongly modulated by the El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and most prominently, the Antarctic Oscillation (AAO). A pronounced decline in rainfall closely parallels a long-term downward trend in the inverted AAO, suggesting the onset of a regional climatic shift.

To further quantify these relationships, a preliminary multivariate moving-window regression analysis was conducted using a wavelet-based continuous low-pass filter applied to the ERA5-L-corrected precipitation dataset, in conjunction with the ENSO, PDO, and inverted AAO indices. Although primarily illustrative rather than climatologically exhaustive, the analysis offers valuable insights into the temporal dominance of different oscillatory modes. As presented in Table V.8, the 1-year window identified ENSO as the most influential short-term modulator ($r = 0.37$), followed by the inverted AAO ($r = 0.35$) and PDO ($r = 0.13$), with all correlations statistically significant at the 0.05 level. Collectively, these indices accounted for approximately 50% of the variability in annual precipitation. Over the 5-year window, the influence of the inverted AAO became more pronounced ($r = 0.60$), exceeding that of PDO ($r = 0.37$) and ENSO ($r = 0.23$), thereby increasing the explained variance to nearly 70%. At the 11-year scale, the inverted AAO emerged as the dominant low-frequency modulator ($r = 0.64$), whereas the contributions from ENSO and PDO declined to approximately 0.15 each.

These findings indicate a progressive shift in the primary drivers of hydrological variability across the region, with the AAO exhibiting increasing dominance since the 1980s. This evolving dynamic—evident in both precipitation and WL patterns—underscores the necessity of incorporating longer-term oscillatory influences such as the AAO into hydrological and

climate modeling for central Chile. Although a comprehensive climatological interpretation lies beyond the scope of this study, the observed trends merit further investigation into the expanding influence of Southern Hemisphere circulation patterns on regional water security.

Table V.8. Summary of Multivariate Moving-Window Regression Analysis: Influence of Climate Oscillations on Precipitation. I-AAO indicates the inverted (negative-phase) Antarctic Oscillation index. All correlation coefficients are significant at the 0.05 level.

Moving Window	Dominant Oscillation	Correlation with Precipitation	Combined R^2 (% Var)
1-year	ENSO (0.37)	ENSO (0.37), I-AAO^{-1} (0.35), PDO (0.13)	~50%
5-year	I-AAO (0.60)	I-AAO (0.60), PDO (0.37), ENSO (0.23)	~70%
11-year	I-AAO (0.64)	I-AAO (0.64), ENSO (0.15), PDO (0.15)	~55%

4.4. Validation of altimetric against in-situ WL series.

Throughout this work, we have created a WL series based on a WB model (Eq. 4) calibrated with altimetric WL observations. In this section, we validate the altimetric data as a reliable control, against in-situ data. We also discuss the potential sources of discrepancy between these two datasets.

Both time-series show similar temporal patterns, as shown in Figure V.5a-b. Both show the same seasonality, evidenced in Figure V.5b, and also in a delay of 9 hours, that could be easily attributed to the location difference (see Figure V.3), and how the water level rises due to the circulation into the

lake. Among the two time-series, there is a *NRMSE* equal to 0.0863, which is inside the acceptable range as discussed in Section 4.2. . The coefficient of determination (R^2 = 0.8573) indicates a strong linear relationship between both datasets, and a Spearman correlation coefficient (s) of 0.8894.

We conclude that the altimetric dataset serves as a reliable proxy when in-situ data is not available.

5. Discussion

5.1. Water level retrieval and forcing

In this study, we developed a conceptual hydrological model that integrates long-term trends and precisely time inputs such as runoff-and-storage and evaporation using datasets from satellite altimetry, GLEV, and environmental reconstructions (ERA5-Land and TerraClimate). The model's performance was validated by statistical metrics, including an R^2 of 0.6920 and a RMSE of 0.4606 against altimetric data, indicating that it effectively captures lake WL variability, although improvements are possible in short-term fluctuation representation. A key innovation of this work is the use of satellite altimetry data, specifically from Sentinel-3A, as a foundational metric for constructing and calibrating the WB model, allowing reconstruction of the long-term WB of the hydrological basin. Our findings align with global trends in lake WL variability driven by teleconnections such as ENSO. However, the growing

influence of the AAO in recent decades sets Lake Lanalhue apart from other systems where ENSO remains the dominant driver..Our aim is to take steps toward creating an automated lake WL monitoring system that eliminates the need for manual preprocessing, such as altimetry data extraction, while effectively representing the basin's environmental history. This is especially important in Chile, where most lakes lack public monitoring systems. To our knowledge, no lake water level data in the study area is publicly provided. Therefore, a conceptual hydrological model using altimetric data as a reference offers a cost-effective alternative to expensive in-situ monitoring programs, providing valuable insights into past lake WL variability.

Our sensitivity analysis shows that precipitation is the dominant factor affecting lake WL, far more than evaporation, as shown in Section 4.2. , highlighting Lake Lanalhue's strong dependence on precipitation, as a typical for pluvially-fed lakes worldwide (Bengtsson, 2012). In central Chile, where rainfall patterns are shifting due to the Megadrought, high precipitation sensitivity underscores the lake's vulnerability to even small changes on it, with concerning implications for water resource management and conservation strategies.

Lake Lanalhue is the only lake in the group of Nahuelbutan lakes covered by available altimetric data, with Sentinel-3A providing the reference measurements of the lake level. The data was instrumental in calibrating the

conceptual hydrological model and ensuring that it accurately reflects the climatic forcing in the region.

The conceptual hydrological model developed in this study (Eq. 4), with considerations in Section 4.1.2.) adequately represents the climatic forcing over the study area. Long-term trends in temperature and evaporation in ERA5-L are consistent with climate change impacts and in-situ data (see Figure V.7c-d). However, ERA5-L does not fully capture the long-term precipitation trend in the study area, which is the primary modulator of the WL. To address this shortfall, we integrated a more accurate long-term trend for precipitation, as detailed in Section 4.1.2. , aligning it with the observed impacts of climate oscillations such as ENSO, PDO, and, in particular, the AAO.

The role of the El Niño–Southern Oscillation (ENSO) in driving interannual variability remains particularly significant, especially in relation to high-frequency precipitation fluctuations. Its pronounced influence on lake water levels over short timescales is consistent with global evidence, as ENSO events are widely recognized for their substantial impact on hydrological systems throughout the Pacific Basin and beyond (Belete et al., 2017). In the 1-year moving-window analysis (see Table V.8), ENSO emerged as the most influential oscillatory mode, underscoring its importance in shaping short-term climate variability in the study region.

However, the moving-window regression analysis also reveals a marked long-term transition: the increasing dominance of the Antarctic Oscillation (AAO) in modulating both interannual and low-frequency variability in precipitation and WL. As shown in Figure V.7 and Table V.8, the inverted AAO accounts for approximately 36% and 41% of the variance over the 5- and 11-year windows, respectively, with corresponding correlation coefficients of 0.60 and 0.64. These results suggest that, since the 1980s, the AAO has progressively emerged as the primary climatic driver of hydrological variability in central Chile. This trend aligns with broader shifts in Southern Hemisphere circulation, where intensifying westerly winds have increasingly migrated poleward, displacing precipitation-bearing systems from mid-latitude regions (Garreaud et al., 2020; Quintana & Aceituno, 2012).

While ENSO and the AAO together explain a substantial portion of observed variability, they account for only about 50% of the total variance at the longest (11-year) timescale. The remaining unexplained component likely reflects non-oscillatory drivers, most notably anthropogenic global warming. As indicated by the persistent warming trends in Figure V.7, long-term changes in atmospheric circulation, jet stream dynamics, and thermodynamic forcing may be contributing to a background signal not captured by traditional oscillatory indices. This interpretation is consistent with IPCC projections, which anticipate continued reductions in winter precipitation across central Chile under future warming scenarios.

The combined influence of natural oscillatory modes and long-term anthropogenic warming presents mounting challenges for water resource management, agriculture, and ecosystem sustainability. Central Chile, already experiencing a sustained decline in winter rainfall, faces intensifying hydroclimatic stress as internal variability interacts with directional climate change. These findings underscore the urgent need for integrated modeling frameworks capable of capturing both high-frequency oscillatory dynamics and long-term climatic trends to inform robust adaptation and planning strategies.

5.2. Anthropic forcing in water balance model

For this model to function as an effective monitoring system, it would ideally represent both climatic and anthropogenic forces, as the latter likely has a great impact on WL. However, at this stage, this model does not account for anthropogenic influences, as explained below.

Anthropogenic impacts on water bodies are predominantly driven by land cover changes. In the study period, the most notable land cover alteration was the expansion of forestry plantations, which accelerated after 1974 (see Section 2.). This change has had a substantial effect on hydrological dynamics, particularly during dry periods, as forestry plantations reduce the capacity to sustain base flow in summer (Lara et al., 2021). However, ERA5-L employs a static climatological land cover, which neither account for urban

expansion nor assume vegetation cover changes (Muñoz-Sabater et al., 2021).

Consequently, the effects of these land-use changes are not captured within the monitoring system. Although this anthropogenic influence cannot be directly observed using the current model, it is highly probable that it plays an important role. To overcome this limitation, future iterations of ERA5-L could incorporate dynamic land cover changes, or alternative databases could be developed with comprehensive long-term coverage of the study area that includes land-use modifications.

The long-term decreasing trend in WL, observed over the reconstruction period in this study, is particularly concerning. While consistent with global patterns, this trend underscores unique regional challenges related to the growing influence of the AAO on precipitation distribution. The decline in WL is likely driven by a combination of reduced precipitation and increased evaporation, the latter exacerbated by rising temperatures. These findings align with broader global climate change impacts, particularly in regions like central Chile, which has been grappling with the persistent Megadrought since 2010. This downward trajectory in WL has profound implications for biodiversity, water availability, and overall ecosystem health, as Lake Lanalhue serves as a vital water resource for the surrounding communities. Although the model successfully captures the climatic factors driving these trends, its

inability to account for anthropogenic factors such as deforestation and land-use changes remains a significant limitation.

Regarding the strengths and limitations of the lake-level reconstruction based on a conceptual hydrological model calibrated with altimetry data, the following can be stated. The calibrated model shows robust performance in describing the long-term variability of Lake Lanalhue's water level. Likewise, the method captures extremes adequately when compared with the altimetry data, which reinforces its usefulness as an approximation when continuous instrumental records are not available. However, its performance shows differences in "timing," departing from the climatological behavior of both the altimetry and in situ datasets. This could be addressed by further developing the hydrological model to include lag parameters linking precipitation, runoff, and changes in lake water level. Likewise, incorporating the effects of land-cover and land-use change would be key.

5.3. Perspectives on this work

In terms of water management and policy, these findings address the urgent need for adaptive strategies that account for the decreasing water availability in critical ecosystems. Policymakers must consider climatic and anthropogenic pressures that are likely to exacerbate these trends. Implementing conservation measures, such as water-use restrictions and the

restoration of native vegetation, can play a crucial role in mitigating the negative impacts, as demonstrated in other regions facing similar challenges.

In Lake Lanalhue, Sentinel-3A provides the reference measurements of the lake level. The data was critical in calibrating the conceptual hydrological model and ensuring that it accurately reflects the climatic forcing in the region.

The monitoring system proposed for Lake Lanalhue can be easily implemented based on the methodology outlined in this study. Its application to other small water bodies will depend on the availability of future in-situ measurements or altimetric data, especially given the higher margin of error associated with smaller lakes and historical missions (Crétaux et al., 2016). However, these limitations may be addressed in the future with the deployment of the large Swath interferometer on the SWOT mission, which allows a much broader vision of inland water bodies, offering sub-decimeter accuracy for lakes larger than 1 km² and possibly with geodetic or drifting orbit missions still under-exploited.

Despite the strengths, our study has certain limitations. As stated before, the conceptual model used does not fully account for anthropogenic influences, such as land-use changes, which can alter lake hydrology. This limitation underscores the need for future research to incorporate detailed land cover data into hydrological models, particularly in regions like central-Chile, where rapid urbanization and deforestation are ongoing. Future studies should

focus on integrating these anthropogenic factors into the modelling framework to provide a more comprehensive understanding of lake level dynamics. Additionally, applying our methodology to other lakes in the Nahuelbuta region and other lake regions in Chile and Argentina would help validate its broader applicability and contribute to a more detailed regional hydrological assessment.

Comparing our results to similar studies on lakes in Africa, the U.S., and Asia underscores the robustness of satellite altimetry as a tool for monitoring lakes in regions where in-situ data scarcity prevents efficient monitoring of inland waters (Crétaux et al., 2016).

This study presents a long-term reconstruction of water levels in Lake Lanalhue, offering valuable insights into its hydrological dynamics in relation to climatic factors, particularly in the absence of in-situ lake level measurements. The practical implications of this research are important: the findings can directly inform adaptive management strategies for Lake Lanalhue, enhancing its resilience in the face of climate change. Furthermore, establishing a simple and replicable monitoring framework will be of great value to water resource managers and policymakers, aiding in the global effort to preserve and sustainably manage critical lake ecosystems.

6. Conclusions

In this study, we successfully reconstructed the long-term water level (WL) of Lake Lanalhue, one of the Nahuelbutan lakes, over the period 1950-2022. This represents the first hydrological reconstruction of its kind within the Nahuelbutan lake basins, located in the Nahuelbuta Mountain Range, a historic biodiversity reserve. Our work contributes significantly to the region's hydrological understanding by providing a key variable, lake water level (WL), in where no in-situ data is available. The methodology presented here is adaptable to other medium- and small-sized lakes lacking in-situ observations, offering a valuable approach for hydrological monitoring in data-scarce environments.

The study reveals a clear seasonal cycle in Lake Lanalhue's WL, primarily driven by the precipitation and its relationship with evaporation. Precipitation peaks in June (winter), followed by a one-month delay in runoff and groundwater storage (July), which suggests a lag in groundwater replenishment. Consequently, the WL reaches its maximum in August, suggesting an additional one-month response period. In spring, precipitation decreases, while temperature and solar radiation increase. In this scenario, evaporation rises, peaking between late December and early January (summer). Subsequently, the WL reaches its minimum in March.

From a long-term perspective, the proposed conceptual hydrological model effectively captures lake water level (WL) dynamics in response to climatic forcing. The influence of climate change is evident in the persistent decline in precipitation and the concurrent increase in evaporation, both driven by increasing regional temperatures. These factors have collectively contributed to a sustained reduction in WL over recent decades, with reduced rainfall and increased evaporative demand as the primary drivers.

Among large-scale climate modes, the El Niño–Southern Oscillation (ENSO) primarily governs the high-frequency component of interannual precipitation variability (1–5 years), while the Antarctic Oscillation (AAO)—and, to a lesser extent, the Pacific Decadal Oscillation (PDO)—modulates lower-frequency interannual trends (5–11 years). Consistent with the findings of Quintana and Aceituno (2012), our results highlight the increasing influence of the AAO, which currently accounts for up to 41% of the variance in precipitation across multi-year windows. Nevertheless, these oscillatory modes collectively explain only about half of the variability at longer timescales (>11 years), suggesting the presence of a substantial residual component likely attributable to anthropogenic climate forcing.

This evolving interplay between natural climate variability and long-term warming reflects a structural transformation in Southern Hemisphere precipitation regimes, posing significant challenges for water resource management in central Chile. Given projections of continued declines in

winter rainfall under future warming scenarios (IPCC, 2021), these findings underscore the urgency of integrating both natural oscillatory processes and anthropogenic trends into hydrological forecasting and climate adaptation strategies.

This study successfully reconstructs Lake Lanalhue's long-term WL and provides valuable insights into the climatic forces shaping its variability. Future research should aim to incorporate anthropogenic influences, such as land-use changes, more explicitly into the modeling framework. Expanding this methodology to other lakes in the Nahuelbuta region and beyond will further illuminate the combined impacts of climate change and human activities on freshwater systems. This study lays the groundwork for the development of an automated lake LWTWL monitoring system for the Nahuelbutan lakes. We hope this research will encourage further exploration of the hydrological cycle in the region and foster restoration efforts aimed at recovering the original land cover of the basins.

Acknowledgements: We would like to thank the anonymous reviewers for their careful scrutiny and insightful suggestions, which greatly enhanced the clarity, rigor, and overall quality of this manuscript. We would also like to thank the editor in charge for their time, guidance, and constructive oversight throughout the review process. We acknowledge the support of the

Laboratoire d'Études en Géophysique et Océanographie Spatiales (LEGOS) in Toulouse, France, for hosting the first author during the development of this research. We also extend our sincere thanks to Dr. Roberto Urrutia from EULA-Chile for providing the essential bathymetric data, which was critical to this study.

Funding: The first author gratefully acknowledges the financial support from ANID BECAS/DOCTORADO NACIONAL Ph.D scholarship (No. 21212143), which also provide funding for a travel grant to LEGOS (Laboratoire d'études en géophysique et océanographie spatiales, Toulouse, France), enabling further research and presentation opportunities related to this study.

Disclosure statement: No potential conflict of interest was reported by the authors.

Appendix V.I: Monitoreo ciudadano de cantidad del agua para su gestión en sistemas lacustres: Experiencias en los Lagos Nahuelbutanos y humedales de la región del Biobío (Chile).

Contexto

La integridad ecológica constituye un marco teórico para evaluar el estado o condición de un sistema socio-ecológico, integrando dimensiones ecológicas, físicas y sociales, entre otras. En el caso de los ecosistemas acuáticos, y particularmente desde una perspectiva hidrológica, este estado se representa a través de indicadores del régimen hidrológico, que dan cuenta de la cantidad del agua dinámica en un sistema y permiten analizar su evolución en el tiempo y su integridad hidrológica. Esta dimensión resulta clave en la gestión del agua, ya que posibilita analizar impactos como inundaciones y sequías. Ejemplos de tales indicadores son el nivel mensual del agua, la duración y el momento de ocurrencia de las crecidas, así como las caídas de nivel en diferentes elevaciones (Gao et al., 2020).

En este trabajo se consideró el nivel del agua del lago como parámetro de integridad hidrológica. De los más de treinta lagos Nahuelbutanos, solamente uno cuenta con monitoreo de nivel del agua por parte de la DGA: el Lago Lanalhue. Si bien es muy valorable que exista este monitoreo y la

inclusión de esta importante variable en él, es necesario extender el monitoreo a otros sistemas lacustres y humedales. Los datos ciudadanos pueden representar una oportunidad, y entre sus aplicaciones destacan el monitoreo, investigación, y aplicación (Metcalfe et al., 2022)

La participación del público general en el diseño de la investigación, la recolección de datos y el proceso de interpretación junto con los científicos se denomina a menudo ciencia ciudadana y ha existido desde los inicios de la práctica científica (Buytaert et al., 2014). Las contribuciones ciudadanas a la ciencia se han implementado con éxito en muchos campos, y los recursos hídricos son uno de ellos (Assumpção et al., 2018; Buytaert et al., 2014; Morales-Magaña et al., 2020). A través de la ciudadanía es posible recopilar datos y lograr un proceso de toma de decisiones más integrado (Assumpção et al., 2018). En el Capítulo II, se relevaron los humedales y lagos como espacios de valor cultural y natural. Los humedales de hecho se entienden como sistemas hidrológicos que deben ser recuperados, como hotspots de biodiversidad que deben preservarse o restaurarse, pero también como territorios hidrosociales que las personas habitan (Choukrani et al., 2023).

Como se habló en el Appendix III.I, en el marco de la Ley de Humedales Urbanos, muchos humedales de la región del Biobío están siendo protegidos. En este proceso, las organizaciones socioambientales han jugado un rol importante, aportando o incluso liderando el proceso de declaratoria. Este proceso, ha sido movido por un valor otorgado a los humedales que va más

allá de lo ecológico: se trata de una relación simbiótica a nivel social, cultural y espiritual. La aparición de conceptos como la sociohidrología indica la creciente relevancia de las conexiones entre las disciplinas sociales e hidrológicas (Seidl & Barthel, 2017). Una de las razones por las que la hidrología ya no puede ignorar que los problemas sociales también influyen en los procesos hidrológicos es la noción de Antropoceno (Seidl & Barthel, 2017). En ese contexto, se implementó en varias lagunas, lagos y humedales del área de estudio y de la Región del Biobío, un sistema de monitoreo participativo de cantidad del agua, que se detalla a continuación.

Proyecto LOCSS

En la región del Biobío (Chile), se estableció una colaboración con el proyecto LOCCS (Mediciones en Lagos Red Ciudadana y Satelital (University of North Carolina, 2025)), financiado por la NASA. El objetivo fue implementar un sistema de monitoreo participativo de cantidad del agua en sistemas lacustres y humedales, con la motivación de levantar datos ambientales, pero también validar tecnologías altimétricas. El proyecto LOCSS busca comprender por qué el volumen de agua en los lagos, lagunas, humedales o ciénagas cambia en el tiempo.

Este trabajo se desarrolló en el marco de esta tesis doctoral, entre 2021 y 2025, gestionado por la autora principal, el profesor guía, y Angélica Gómez, del proyecto LOCSS. Como asociadas al proyecto participaron las

Universidades de North Carolina, de Concepción y Santo Tomás. Así mismo, las organizaciones socio-ambientales Red de Humedales Bíobío, Corporación Junquillar, Agrupación para la Conservación Laguna Junquillar, Agrupación Denavi Sur; la entidad privada Campos Deportivos Llacolén y la iniciativa estatal PRELA.

Durante la ejecución de este proyecto se instalaron regletas de medición del nivel del agua del lago, que funcionan con monitoreo participativo (Figure V.8), en los siguientes sistemas lacustres, humedales y esteros: Estero Los Batros, Humedal Denavi Sur, Lago Lanalhue, Laguna Antihuala, Laguna Chica de San Pedro, Laguna Grande San Pedro, Laguna Junquillar, Laguna Lo Custodio. Todos ellos están ubicados en la región del Biobío y la mayor parte de ellos, exceptuando el Humedal Denavi Sur y la Laguna Lo Custodio, se originan por efecto de la Cordillera de Nahuelbuta.



Figure V.8. Regleta de medición del nivel del agua en Laguna Junquillar.

Datos ciudadanos en la gestión ambiental

De las regletas instaladas, los tres casos que mejor funcionaron, donde la toma de datos ha sido frecuente, y donde el sistema ha tenido continuidad desde su instalación, son los casos del Humedal Denavi Sur, Laguna Junquillar y Laguna Lo Custodio. Las dos primeras, están asociados a una organización socioambiental y comunidad humana que habita el lugar, y que,

por lo tanto, el sistema natural es parte de su vida y actividades. El tercero es parte de una investigación doctoral, por lo que ha habido un equipo permanentemente atento de tomar las medidas.

El resto de los casos, funcionaron muy poco, otros funcionaron muy bien por un tiempo, pero se discontinuaron. Las razones podrían ser las siguientes. I) Se dañó la infraestructura de la regleta. Ii) Son lugares privados que la comunidad no habita cotidianamente y por lo tanto ese lugar no forma parte de su vida y sus actividades. Iii) La comunidad si habita el lugar, pero no hay un grupo específico que se ocupe permanentemente de la gestión del sistema.

En cuanto a estos resultados, existen algunas recomendaciones para que los monitoreos ciudadanos sean exitosos. Por ejemplo, en San Llorente Capdevila et al. (2020), se mencionan atributos de los ciudadanos (ej.: conocimiento, experiencia, motivación) (ii) atributos de las instituciones (motivación, tipo de organización, financiamiento, constancia), (iii) interacciones entre ciudadanos e instituciones (estructura de apoyo, comunicación, retroalimentación).

Lo anterior da cuenta de la necesidad de soporte estructural de la iniciativa, a nivel ciudadano, pero también a nivel institucional, o en la investigación que se esté desarrollando. Esto representa una oportunidad

para que este tipo de ciencia trabaje articuladamente con las instituciones para combatir la degradación ambiental mediante la restauración socio ecológica.

References

Abarca-Del-Rio, R., CrÉtaux, J.-F., Berge-Nguyen, M., & Maisongrande, P. (2012). Does Lake Titicaca still control the Lake Poopó system water levels? An investigation using satellite altimetry and MODIS data (2000–2009). *Remote Sensing Letters*, *3*(8), 707-714. https://doi.org/10.1080/01431161.2012.667884

Abarzúa et al. (2020). *Informe final: Análisis de Testigo Sedimentari... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Informe%20final%3A%20An%C3%A1lisis%20de%20Testigo%20Sedimentario%20en%20Lago%20Lanalhue%2C%20Provincia%20de%20Arauco%2C%20Regi%C3%B3n%20del%20Biob%C3%ADo&author=A.M.%20Abarz%C3%BAa&publication_year=2020

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, *5*(1), 170191. https://doi.org/10.1038/sdata.2017.191

Abubakar, H. B. (2024). *Evaluation of high-resolution precipitation datasets CHIRPS, TerraClimate and TAMSAT over the Enkangala Escarpment of South Africa*. Research Square. https://doi.org/10.21203/rs.3.rs-4365508/v1

Adjovu, G. E., Stephen, H., James, D., & Ahmad, S. (2023). Overview of the Application of Remote Sensing in Effective Monitoring of Water Quality Parameters. *Remote Sensing*, *15*(7), 1938. https://doi.org/10.3390/rs15071938

Afsharian, S., & Taylor, P. A. (2019). On the Potential Impact of Lake Erie Wind Farms on Water Temperatures and Mixed-Layer Depths: Some Preliminary 1-D Modeling Using COHERENS. *Journal of Geophysical Research: Oceans*, *124*(3), 1736-1749. https://doi.org/10.1029/2018JC014577

Agência Nacional de Águas. (2010). *NORMAS DE COBRANÇA PELO USO DE RECURSOS HÍDRICOS*. https://www.ana.gov.br/arquivos/institucional/sge/CEDOC/Catalogo/2010/NormasDeCobrancaPeloUsoDosRecursosHidricos2010.pdf

Agência Nacional de Águas e Saneamento Básico (ANA). (2025). *Qualidade da água*. https://www.gov.br/ana/pt-br/assuntos/monitoramento-e-eventos-criticos/qualidade-da-agua/qualidade-da-agua

Aguayo Arias, M. I. (2008). *El cambio de uso del suelo en el centro sur de Chile. Comprendiendo su dinámica a través de la modelación espacialmente explícita y explorando sus efectos ambientales en una cuenca hidrológica de meso escala.* [[PhD Thesis], Universidad de Concepción]. https://repositorio.udec.cl/handle/11594/6004

Aguayo, M., Pauchard, A., Azócar, G., & Parra, O. (2009). Cambio del uso del suelo en el centro sur de Chile a fines del siglo XX: Entendiendo la dinámica espacial y temporal del paisaje. *Revista chilena de historia natural*, *82*(3), 361-374.

Alaniz, A. J., Abarzúa, A. M., Martel-Cea, A., Jarpa, L., Hernández, M., Aquino-López, M. A., & Smith-Ramírez, C. (2021). Linking sedimentological and spatial analysis to assess the impact of the forestry industry on soil loss: The case of Lanalhue Basin, Chile. *CATENA*, *207*, 105660. https://doi.org/10.1016/j.catena.2021.105660

Alaniz, A. J., Smith-Ramírez, C., Rendón-Funes, A., Hidalgo-Corrotea, C., Carvajal, M. A., Vergara, P. M., & Fuentes, N. (2022). Multiscale spatial analysis of headwater vulnerability in South-Central Chile reveals a high threat due to deforestation and climate change. *Science of The Total Environment*, *849*, 157930. https://www.sciencedirect.com/science/article/pii/S004896972205029X

Albus, K. H., Thompson, R., Mitchell, F., Kennedy, J., & Ponette-González, A. G. (2020). Accuracy of long-term volunteer water monitoring data: A multiscale analysis from a statewide citizen science program. *PLOS ONE*, *15*(1), e0227540. https://doi.org/10.1371/journal.pone.0227540

Alfonso, L., Gharesifard, M., & Wehn, U. (2022). Analysing the value of environmental citizen-generated data: Complementarity and cost per observation. *Journal of Environmental Management*, *303*, 114157. https://doi.org/10.1016/j.jenvman.2021.114157

Allan, M. G., Hamilton, D. P., Trolle, D., Muraoka, K., & McBride, C. (2016). Spatial heterogeneity in geothermally-influenced lakes derived from atmospherically corrected Landsat thermal imagery and three-dimensional hydrodynamic modelling. *International Journal of Applied Earth Observation and Geoinformation*, *50*, 106-116. https://doi.org/10.1016/j.jag.2016.03.006

Almanza, V., Parra, O., De M. Bicudo, C. E., Baeza, C., Beltran, J., Figueroa, R., & Urrutia, R. (2016). Occurrence of toxic blooms of Microcystis aeruginosa in a central Chilean (36° Lat. S) urban lake. *Revista Chilena de Historia Natural*, *89*(1), 8. https://doi.org/10.1186/s40693-016-0057-7

Altieri, M. A., & Rojas, A. (1999). Ecological Impacts of Chile's Neoliberal Policies, with Special Emphasis on Agroecosystems. *Environment, Development and Sustainability*, *1*(1), 55-72.

Altman, D. G. (1990). *Practical Statistics for Medical Research*. Chapman and Hall/CRC. https://doi.org/10.1201/9780429258589

Alvial Vásquez, F.-J., Abarca-del-Río, R., & Ávila, A. I. (2020). High-Resolution Precipitation Gridded Dataset on the South-Central Zone (34° S–41° S) of Chile. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.519975

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M., Moghaddam, S. H. A., Mahdavi, S., Ghahremanloo, M., Parsian, S., Wu, Q., & Brisco, B. (2020). Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 5326-5350. https://doi.org/10.1109/JSTARS.2020.3021052

Amour, I., & Kauranne, T. (2017). A variational ensemble Kalman filtering method for data assimilation using 2D and 3D version of COHERENS model. *International Journal for Numerical Methods in Fluids*, *83*(6), 544-558. https://doi.org/10.1002/fld.4276

Angrosino, M. (2012). *Etnografía y observación participante en Investigación Cualitativa*. Ediciones Morata.

Araos, F., Catalán, E., Nuñez, D., Riquelme, W., Cortinez, V., de Fina, D., & Anbleyth-Evans, J. (2023). Cuidando la Patagonia Azul: Prácticas y estrategias de los pueblos originarios para curar las zonas marinas del sur de Chile. *The Journal of Latin American and Caribbean Anthropology*, *28*(4), 286-297. https://onlinelibrary.wiley.com/doi/abs/10.1111/jlca.12695

Araya. (2019). *Desafíos del turismo y la conservación de la biodiversidad* (Primera edición, septiembre de 2019). Amukan Editorial itinerante.

Ardiantiono, Deere, N. J., Seaman, D. J. I., Mamat Rahmat, U., Ramadiyanta, E., Lubis, M. I., Trihangga, A., Yasin, A., Alza, G., Sari, D. P., Daud, M., Abdullah, R., Mutia, R., Melvern, D., Tarmizi, Supriatna, J., & Struebig, M. J. (2025). Improved cost-effectiveness of species monitoring programs through data integration. *Current Biology*, *35*(2), 391-397.e3. https://doi.org/10.1016/j.cub.2024.11.051

Argyilan, E. P., & Forman, S. L. (2003). Lake Level Response to Seasonal Climatic Variability in the Lake Michigan-Huron System from 1920 to 1995. *Journal of Great Lakes Research*, *29*(3), 488-500. https://doi.org/10.1016/S0380-1330(03)70453-5

Aróstegui, M. G. (2001). Cultura de la resistencia. Concepciones teóricas y metodológicas para su estudio. *Islas*, (127), 20-41. http://islas.uclv.edu.cu/index.php/islas/article/download/721/646

Arroyo, M. T. K. (2006). *El hotspot chileno, prioridad mundial para la conservación. Diversidad de ecosistemas, ecosistemas terrestres*.

Arsen, A., Crétaux, J.-F., Berge-Nguyen, M., & Del Rio, R. A. (2014). Remote Sensing-Derived Bathymetry of Lake Poopó. *Remote Sensing*, *6*(1), 407-420. https://doi.org/10.3390/rs6010407

Ascencio, E., Rivera, P., Cruces, F., Vila, I., Ascencio, E., Rivera, P., Cruces, F., & Vila, I. (2018). Estudio morfológico de Naiadinium polonicum (Dinophyceae) reportado por primera vez en aguas continentales de Chile. *Gayana. Botánica*, *75*(1), 438-446. https://doi.org/10.4067/S0717-66432018000100438

Assumpção, T. H., Popescu, I., Jonoski, A., & Solomatine, D. P. (2018). Citizen observations contributing to flood modelling: Opportunities and challenges. *Hydrology and Earth System Sciences*, *22*(2), 1473-1489. https://doi.org/10.5194/hess-22-1473-2018

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., Van Den Hurk, B., Hirschi, M., & Betts, A. K. (2009). A Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System. *Journal of Hydrometeorology*, *10*(3), 623-643. https://doi.org/10.1175/2008JHM1068.1

Banco Central de Chile. (2025). *Base de Datos Estadísticos (BDE)*. https://si3.bcentral.cl/siete/ES/Siete/Cuadro/CAP_CCNN/MN_CCNN76/CCNN_EP18_05_ratio

Baracchini, T., Hummel, S., Verlaan, M., Cimatoribus, A., Wüest, A., & Bouffard, D. (2020). An automated calibration framework and open source tools for 3D lake hydrodynamic models. *Environmental Modelling & Software*, *134*, 104787. https://doi.org/10.1016/j.envsoft.2020.104787

Barría, P., Chadwick, C., Ocampo-Melgar, A., Galleguillos, M., Garreaud, R., Díaz-Vasconcellos, R., Poblete, D., Rubio-Álvarez, E., & Poblete-Caballero, D.

(2021). Water management or megadrought: What caused the Chilean Aculeo Lake drying? *Regional Environmental Change*, *21*(1), 19. https://doi.org/10.1007/s10113-021-01750-w

Barros Delgado, B. B. J. (2022). *Dinámica de los asentamientos rurales y su relación con la expansión forestal en las comunas de Curanilahue, Lebu y Los Álamos, entre el periodo 1960—2002*. https://repositorio.uchile.cl/handle/2250/188639

Batina, A., & Krtalić, A. (2024). Integrating Remote Sensing Methods for Monitoring Lake Water Quality: A Comprehensive Review. *Hydrology*, *11*(7), 92. https://doi.org/10.3390/hydrology11070092

BCN. (2024). *Biblioteca del Congreso Nacional de Chile. Glosario de términos geográficos*. https://www.bcn.cl/siit/glosario/index_html

BCNa. (2024). *Reporte Comunal—Biblioteca del Congreso Nacional de Chile*. https://www.bcn.cl/siit/reportescomunales/comunas_v.html?anno=2023&idcom=8108

BCNb. (2017). *Buscador Estadístico—SIIT*. https://www.bcn.cl/siit/estadisticasterritoriales//resultados-consulta?id=326233

BCNc. (2024). *Chile: Población censada y tasas de crecimiento medio anual, según ciudades, 1950-2002*. https://www.memoriachilena.gob.cl/602/w3-article-74944.html

Beguería, S., Vicente Serrano, S. M., Reig-Gracia, F., & Latorre Garcés, B. (2023). *SPEIbase v.2.9 [Dataset]* [Dataset]. DIGITAL.CSIC. https://doi.org/10.20350/digitalCSIC/15470

Belete, M. D., Diekkrüger, B., & Roehrig, J. (2017). Linkage between Water Level Dynamics and Climate Variability: The Case of Lake Hawassa Hydrology and ENSO Phenomena. *Climate*, *5*(1), 21. https://doi.org/10.3390/cli5010021

Bengoa, J. (2000). *Historia del pueblo mapuche: (Siglo XIX y XX)*. Lom Ediciones.

Bengtsson, L. (2012). Water Balance of Lakes. En L. Bengtsson, R. W. Herschy, & R. W. Fairbridge (Eds.), *Encyclopedia of Lakes and Reservoirs* (pp. 863-864). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4410-6_18

Betts, A. K., Reid, D., & Crossett, C. (2020). Evaluation of the FLake Model in ERA5 for Lake Champlain. *Frontiers in Environmental Science*, *8*. https://doi.org/10.3389/fenvs.2020.609254

Beutel, M. W., Horne, A. J., Roth, J. C., & Barratt, N. J. (2001). Limnological effects of anthropogenic desiccation of a large, saline lake, Walker Lake, Nevada. *Hydrobiologia*, *466*(1), 91-105. https://doi.org/10.1023/A:1014569521381

Biblioteca del Congreso Nacional. (2021, octubre 13). *Biblioteca del Congreso Nacional | Ley Chile*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Biblioteca del Congreso Nacional. (2023, septiembre 6). *Ley 21600 CREA EL SERVICIO DE BIODIVERSIDAD Y ÁREAS PROTEGIDAS Y EL SISTEMA NACIONAL DE ÁREAS PROTEGIDAS*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Bio Bio (Director). (2023, febrero 13). *Dichos de Boric por regulación de industria forestal fueron catalogados como «fuera de contexto»* [Video recording]. https://www.youtube.com/watch?v=do0zHOXR5Us

Bolados, P., Espinoza, L., & Panez, A. (2024). Una aproximación decolonial a las Zonas de Sacrificio en Chile. *Vibrant: Virtual Brazilian Anthropology*, *21*, e21603. https://www.scielo.br/j/vb/a/vtQ6tPk9TWjThNfhNJTLtcv/?lang=es

Bongioannini Cerlini, P., Saraceni, M., Silvestri, L., Meniconi, S., & Brunone, B. (2022). Monitoring the Water Mass Balance Variability of Small Shallow Lakes by an ERA5-Land Reanalysis and Water Level Measurement-Based Model. An Application to the Trasimeno Lake, Italy. *Atmosphere*, *13*(6), Article 6. https://doi.org/10.3390/atmos13060949

Bonney, P. R., Hansen, B. D., & Baldwin, C. (2023). Citizen Science and Natural Resource Management: A Social Network Analysis of Two Community-Based Water Monitoring Programs. *Society & Natural Resources*, *36*(6), 600-621. https://doi.org/10.1080/08941920.2023.2183445

Boy, F., Crétaux, J.-F., Boussaroque, M., & Tison, C. (2022). Improving Sentinel-3 SAR Mode Processing Over Lake Using Numerical Simulations. *IEEE Transactions on Geoscience and Remote Sensing*, *60*, 1-18. https://doi.org/10.1109/TGRS.2021.3137034

Bravo Ferretti, C., Sandoval-Díaz, J., Astudillo Pizarro, F., Bravo Ferretti, C., Sandoval-Díaz, J., & Astudillo Pizarro, F. (2022). Narrativas del acorralamiento. Identidad de Lugar en la Bahía de Coronel a partir de la reconversión productiva. *Revista de historia (Concepción)*, *29*(1), 73-105. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-88322022000100073&lng=es&nrm=iso&tlng=en

Bravo Orrego, C. M. (2018). *Caracterización de la precipitación en la Cordillera de Nahuelbuta según la microfísica bajo la cual ocurre* [[PhD Thesis], Universidad de Chile]. https://repositorio.uchile.cl/handle/2250/168171

Brown, C. F., Brumby, S. P., Guzder-Williams, B., Birch, T., Hyde, S. B., Mazzariello, J., Czerwinski, W., Pasquarella, V. J., Haertel, R., Ilyushchenko, S., Schwehr, K., Weisse, M., Stolle, F., Hanson, C., Guinan, O., Moore, R., & Tait, A. M. (2022). Dynamic World, Near real-time global 10 m land use land cover mapping. *Scientific Data*, *9*(1), 251. https://www.nature.com/articles/s41597-022-01307-4

Budds, J. (2013). Water, Power, and the Production of Neoliberalism in Chile, 1973–2005. *Environment and Planning D: Society and Space*, *31*(2), 301-318. https://doi.org/10.1068/d9511

Burić, D., & Penjišević, I. (2023). Southern Hemisphere temperature trend in association with greenhouse gases, El Niño Southern Oscillation, and Antarctic Oscillation. *Időjárás*, *127*(1), 23-42. https://doi.org/10.28974/idojaras.2023.1.2

Burns, N. (2020). *Protocol for Monitoring Trophic Levels of New Zealand Lakes and Reservoirs*.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, *2*. https://www.frontiersin.org/articles/10.3389/feart.2014.00026

Carlson, R. E. (1977). A trophic state index for lakes. *Limnology and Oceanography*, *22*(2), 361-369. https://doi.org/10.4319/lo.1977.22.2.0361

Carmona, A., & Nahuelhual, L. (2012). Combining land transitions and trajectories in assessing forest cover change. *Applied Geography*, *32*(2), 904-915. https://www.sciencedirect.com/science/article/pii/S0143622811001755

Caro, C. S. M. (2003). *Aproximación a las estrategias de sobrevivencia de las familias de la caleta de Boca Sur Viejo en San Pedro de la Paz; experiencia y estudio de caso* [[PhD Thesis]]. Universidad de Concepción.

Carrasco Henríquez, N., & Mendoza Leal, C. (2021). Restoration as a re-commoning process. Territorial initiative and global conditions in the process of water recovery in the 'Cordillera de Nahuelbuta', Chile. *Ecosystems and People*, *17*(1), 556-573. https://doi.org/10.1080/26395916.2021.1993345

Castillo, S. F. (s. f.). *Ciudad y el derecho al buen vivir: Contribución rural a la reconstrucción de espacios fragmentados Barrio Boca Sur, Concepción, Chile.*

Chazdon, R. L., Falk, D. A., Banin, L. F., Wagner, M., J. Wilson, S., Grabowski, R. C., & Suding, K. N. (2024). The intervention continuum in restoration ecology: Rethinking the active–passive dichotomy. *Restoration Ecology*, *32*(8), e13535. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.13535

Cheng, C., Du, W., Li, J., Bao, A., Ge, W., Wang, S., Ma, D., & Pan, Y. (2023). Spatiotemporal Variations of Glacier Mass Balance in the Tomur Peak Region Based on Multi-Source Altimetry Remote Sensing Data. *Remote Sensing*, *15*(17), 4143. https://doi.org/10.3390/rs15174143

Cheng, C., Xing, Z., Ye, L., Yang, J., & Xie, Z. (2024). Characteristics and Influencing Factors of Landscape Pattern Gradient Transformation of Small-Scale Agroforestry Patches in Mountain Cities. *Sustainability*, *16*(15), 6322. https://doi.org/10.3390/su16156322

Chicco, D., Warrens, M. J., & Jurman, G. (2021). The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Computer Science*, *7*, e623. https://doi.org/10.7717/peerj-cs.623

Chile_ING_ESP.xls. (s. f.). Recuperado 25 de julio de 2025, de https://www.memoriachilena.gob.cl/archivos2/pdfs/MC0018840.PDF

Choongik, C. (2025). Unequal Distribution of Climate Change Impacts across Regions: Towards Climate Justice. *Journal of Distribution Science*, *23*(4), 103-116. https://koreascience.kr/article/JAKO202512250404430.page

Choukrani, H., Lacombe, G., Zwarteveen, M., Kuper, M., Taky, A., & Hammani, A. (2023). Sense-making and shaping of temporary wetlands: A socio-hydrological analysis of dichotomous ontologies of merjas in Morocco. *Journal of Hydrology*, 130434. https://doi.org/10.1016/j.jhydrol.2023.130434

Clark, B., & York, R. (2008). Rifts and Shifts: Getting to the Root of Environmental Crises. *Monthly Review*, *60*(6), 13. http://archive.monthlyreview.org/index.php/mr/article/view/MR-060-06-2008-10_2

Clark, N. E., Eber, L. E., Laurs, R. M., Renneer, J. A., & Saur, J. F. T. (1974). *Heat exchange between ocean and atmosphere in the eastern North Pacific for 1961-71*. https://repository.library.noaa.gov/view/noaa/11864/noaa_11864_DS1.pdf

Clark, & York. (2005). Carbon metabolism: Global capitalism, climate change, and the biospheric rift. *Theory and Society*, *34*(4), 391-428. https://doi.org/10.1007/s11186-005-1993-4

CNES. (2015). *How altimetry works [online]. Toulouse, Centre national d'études spatiales (CNES)*. https://cnes.fr/en/how-altimetry-works

Comisión Presidencial para la Paz y el Entendimiento. (2025). *Resumen ejecutivo de las recomendaciones al Estado de Chile en materia de tierras y derechos del pueblo Mapuche*. Ministerio Secretaría General de la Presidencia. https://www.comisionpazyentendimiento.gob.cl/wp-content/uploads/2025/05/Resumen-Ejecutivo-Oficial-Cierre-Comision-para-la-Paz-y-el-Entendimiento.pdf

Condom, T., Martínez, R., Pabón, J. D., Costa, F., Pineda, L., Nieto, J. J., López, F., & Villacis, M. (2020). Climatological and Hydrological Observations for the South American Andes: In situ Stations, Satellite, and Reanalysis Data Sets. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.00092

Congalton, R. G., Gu, J., Yadav, K., Thenkabail, P., & Ozdogan, M. (2014). Global Land Cover Mapping: A Review and Uncertainty Analysis. *Remote Sensing*, *6*(12), 12070-12093. https://doi.org/10.3390/rs61212070

COPERNICUS. (2025). *Land Monitoring Service: Temperature and Reflectance*. https://land.copernicus.eu/en/products/temperature-and-reflectance

Corporación Junquillar. (2024). *Protocolo de monitoreo de calidad del agua en la Laguna Junquillar*.

Corporación Junquillar. (2025). *Laguna Junquillar (@lagunajunquillar) • Fotos y videos de Instagram*. https://www.instagram.com/lagunajunquillar/

Correa, M. (2021). La Historia del Despojo; El Origen de la Propiedad Particular en el Territorio. *Santiago, Chile: Ceibo-Pehuén Ediciones*.

Cosgrove, A., & Berkelhammer, M. (2018). Downwind footprint of an urban heat island on air and lake temperatures. *Npj Climate and Atmospheric Science*, *1*(1), 46. https://doi.org/10.1038/s41612-018-0055-3

(CR)2. (2025). *Explorador climático (CR)2* (Available online) [Dataset]. https://explorador.cr2.cl/

Cretaux, J., Kouraev, A., Papa, F., Bergé-Nguyen, M., Cazenave, A., Aladin, N., & Plotnikov, I. (2005). *Water balance of the Big Aral Sea from satellite remote sensing and in situ observations*. *31*.

Crétaux, J.-F., Abarca-del-Río, R., Bergé-Nguyen, M., Arsen, A., Drolon, V., Clos, G., & Maisongrande, P. (2016). Lake Volume Monitoring from Space. *Surveys in Geophysics*, *37*(2), 269-305. https://doi.org/10.1007/s10712-016-9362-6

Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011a). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011b). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., & Birkett, C. (2006). Lake studies from satellite radar altimetry. *Comptes Rendus Geoscience, La Terre observée depuis l'espace*, *338*(14), 1098-1112. https://doi.org/10.1016/j.crte.2006.08.002

CTOH. (2024, julio 10). *Altimetric Time Series Software (AITiS) [software]*. GitLab. https://gitlab.com/ctoh/altis

Cuomo, C. J. (2011). Climate change, vulnerability, and responsibility. *Hypatia*, *26*(4), 690-714.

Da Silva, J. S., Seyler, F., Calmant, S., Rotunno Filho, O. C., Roux, E., Araújo, A. A. M., & Guyot, J. L. (2012). Water level dynamics of Amazon wetlands at the watershed scale by satellite altimetry. *International Journal of Remote Sensing*, *33*(11), 3323-3353. https://doi.org/10.1080/01431161.2010.531914

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018a). Understanding the abrupt climate change in the mid-1970s from a phase-space transform perspective. *Journal of Applied Meteorology and Climatology*, *57*(11), 2551-2560. https://journals.ametsoc.org/view/journals/apme/57/11/jamc-d-17-0345.1.xml

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018b). *Understanding the Abrupt Climate Change in the Mid-1970s from a Phase-Space Transform Perspective*. https://doi.org/10.1175/JAMC-D-17-0345.1

Davidson, N. C., Fluet-Chouinard, E., & Finlayson, C. M. (2018). Global extent and distribution of wetlands: Trends and issues. *Marine and Freshwater Research*, *69*(4), 620-627. https://www.publish.csiro.au/mf/MF17019

Delgado, F., & Rist. (2016). *Las ciencias desde la perspectiva del diálogo de saberes, la transdisciplinariedad y el diálogo intercientífico*.

Deltares. (2025). *Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments User Manual Hydro-Morphodynamics Version: 4.05.* https://www.google.com/search?q=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&oq=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBBzQxOWowajSoAgCwAgE&sourceid=chrome&ie=UTF-8

DGA. (2025a). *Red hidrométrica en línea DGA.* [Dataset]. https://dga.mop.gob.cl/servicioshidrometeorologicos/Paginas/default.aspx

DGA. (2025b). *Sistema Hidrométrico en Línea | Dirección General de Aguas*. https://dga.mop.gob.cl/sistema-hidrometrico-en-linea/

Di Chiro, G. (2015). A New Spelling Of Sustainability: Engaging Feminist-Environmental Justice Theory And Practice. *Practising Feminist Political Ecologies: Moving Beyond The «Green Economy»*, 211-236. https://doi.org/10.5040/9781350221970.ch-007

Echeverría, C., Bolados, G., Rodriguez, J., Aguayo, M., & Premoli, A. (s. f.). Ecología de Paisajes Forestales. *2014*.

ECMWF. (2020). *ECMWF Confluence Wiki: 3.3. OpenIFS: Surface Model HTESSEL [online]. Reading, European Centre for Medium-Range Weather Forecasts (ECMWF).* https://confluence.ecmwf.int/display/OIFS/3.3+OpenIFS%3A+Surface+Model+HTESSEL

ECMWF. (2025). *ERA5: Data documentation—Copernicus Knowledge Base—ECMWF Confluence Wiki*. https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation

ECMWF/C3S. (2024a). *Earth Engine Data Catalog: ERA5 Monthly Aggregates [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#bands

ECMWF/C3S. (2024b). *Earth Engine Data Catalog: ERA5-Land Monthly Aggregated [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR

ECOMOD. (2025). *COHERENS modelling system. ECOMOD – Marine Ecosystem Modelling*. https://ecomod.be/projects/COHERENS/

EEDC. (2025a). *USGS Landsat 8 Level 2, Collection 2, Tier 1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

EEDC. (2025b). *WorldClim Climatology V1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/WORLDCLIM_V1_MONTHLY?hl=es-419

EEDCa. (2025). *USGS Landsat 8 Collection 2 Tier 1 and Real-Time data Raw Scenes* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_RT?hl=es-419

EEDCb. (2025). *USGS Landsat 8 Collection 2 Tier 1 TOA Reflectanc* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_TOA?hl=es-419

EEDCc. (2025). *USGS Landsat 8 Level 2, Collection 2, Tier 1* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

Elachi, C., & Van Zyl, J. J. (2006). Introduction to the physics and techniques of remote sensing. John Wiley and Sons. *New Jersey. USA 513p*.

Elachi, C., & Zyl, J. J. van. (2021). *Introduction to the Physics and Techniques of Remote Sensing*. John Wiley & Sons.

EMOL, E. M. (2023, febrero 13). *Monsalve y debate abierto por Boric sobre industria forestal: «Sería irracional que la sociedad no diera una discusión»*. Emol. https://www.emol.com/noticias/Nacional/2023/02/13/1086588/monsalve-industria-forestal.html

EROS. (2022, noviembre 9). *USGS EROS Archive—Landsat Archives—Landsat 8-9 OLI/TIRS Collection 2 Level-2 Science Products | U.S. Geological Survey*. https://www.usgs.gov/centers/eros/science/usgs-eros-archive-landsat-archives-landsat-8-9-olitirs-collection-2-level-2

ESA. (2025a). *ATSR Reprocessing for Climate: Lake Surface Water Temperature & Ice Cover (ARC-Lake)*. https://datashare.ed.ac.uk/handle/10283/88

ESA. (2025b). *Summary of RESETlakes (REmote SEnsing of Tipping points in Lakes)*. ESA Climate Office. https://climate.esa.int/en/tipping-points-research/about-resetlakes/about-resetlakes/

European Environment Agency. (2018, julio 3). *Quality element status*. https://www.eea.europa.eu/en/analysis/maps-and-charts/quality-elements-of-water-bodies-water-assessments

Falkenmark, M., & Rockström, J. (2004). *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. Earthscan.

Falvey, M., & Garreaud, R. D. (2009). Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). *Journal of Geophysical Research: Atmospheres*, *114*(D4). https://doi.org/10.1029/2008JD010519

Fang, G. H., Yang, J., Chen, Y. N., & Zammit, C. (2015). Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, *19*(6), 2547-2559. https://doi.org/10.5194/hess-19-2547-2015

Fang, X., & An, D. (2022). Evaluation on sea surface wind speed product of Fengyun-3D satellite microwave radiation imager using ERA-5 dataset. *International Journal of Remote Sensing*, *43*(10), 3671-3691. https://doi.org/10.1080/01431161.2022.2099770

Fang, X., & Stefan, H. G. (1996). Dynamics of heat exchange between sediment and water in a lake. *Water Resources Research*, *32*(6), 1719-1727. https://doi.org/10.1029/96WR00274

FAO. (2025). *NEW! Check out the Open Foris interactive story*. OpenForis. https://www.fao.org/in-action/openforis/en

Farnaz Nojavan, F. N., Kreakie, B. J., Hollister, J. W., & Qian, S. S. (2019). Rethinking the lake trophic state index. *PeerJ*, *7*, e7936. https://doi.org/10.7717/peerj.7936

Fatichi, S. (2025, agosto 1). *Mann-Kendall Test (https://www.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test), MATLAB Central File Exchange. Recuperado 1 agosto, 2025.* https://la.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test

Fernández, I. C., Manuel-Navarrete, D., & Torres-Salinas, R. (2016). Breaking resilient patterns of inequality in Santiago de Chile: Challenges to navigate towards a more sustainable city. *Sustainability*, *8*(8), 820. https://www.mdpi.com/2071-1050/8/8/820

Fernández-Manjarrés, J. F., Roturier, S., & Bilhaut, A.-G. (2018). The emergence of the social-ecological restoration concept. *Restoration Ecology*, *26*(3), 404-410. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.12685

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302-4315. https://doi.org/10.1002/joc.5086

Fischer, R., Tamayo Cordero, F., Ojeda Luna, T., Ferrer Velasco, R., DeDecker, M., Torres, B., Giessen, L., & Günter, S. (2021). Interplay of governance elements and their effects on deforestation in tropical landscapes: Quantitative insights from Ecuador. *World Development*, *148*, 105665. https://www.sciencedirect.com/science/article/pii/S0305750X21002801

Fitchett, L. L., Sorice, M. G., Cobourn, K. M., Boyle, K. J., Klug, J. L., & Weathers, K. C. (2020). Pathways to enhanced lake integrity: A Framework to assess the effectiveness of local lake associations. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *25*(2), 258-268. https://doi.org/10.1111/lre.12308

Flavelle, A. (2003). *Mapping Our Land: Community Mapping Handbook*. Lone Pine.

Fluet-Chouinard, E., Stocker, B. D., Zhang, Z., Malhotra, A., Melton, J. R., Poulter, B., Kaplan, J. O., Goldewijk, K. K., Siebert, S., Minayeva, T., Hugelius, G., Joosten, H., Barthelmes, A., Prigent, C., Aires, F., Hoyt, A. M., Davidson, N., Finlayson, C. M., Lehner, B., … McIntyre, P. B. (2023). Extensive global wetland loss over the past three centuries. *Nature*, *614*(7947), 281-286. https://www.nature.com/articles/s41586-022-05572-6

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R., Chapin, F. S., Seto, K. C., Weber, E. U., Crona, B. I., Daily, G. C., Dasgupta, P., Gaffney, O., Gordon, L. J., Hoff, H., Levin, S. A., … Walker, B. H. (2021). Our future in the Anthropocene biosphere. *Ambio*, *50*(4), 834-869. https://doi.org/10.1007/s13280-021-01544-8

Foster, J. B. (2022). *Capitalism in the Anthropocene: Ecological Ruin or Ecological Revolution*. NYU Press.

Foster, J. B., Clark, B., & York, R. (2011). *The Ecological Rift: Capitalism's War on the Earth*. NYU Press.

Frappart, F., Blarel, F., Fayad, I., Bergé-Nguyen, M., Crétaux, J.-F., Shu, S., Schregenberger, J., & Baghdadi, N. (2021). Evaluation of the Performances of Radar and Lidar Altimetry Missions for Water Level Retrievals in Mountainous Environment: The Case of the Swiss Lakes. *Remote Sensing*, *13*(11), 2196. https://doi.org/10.3390/rs13112196

Frassl, M. A., Boehrer, B., Holtermann, P. L., Hu, W., Klingbeil, K., Peng, Z., Zhu, J., & Rinke, K. (2018). Opportunities and Limits of Using Meteorological Reanalysis Data for Simulating Seasonal to Sub-Daily Water Temperature Dynamics in a Large Shallow Lake. *Water*, *10*(5), Article 5. https://doi.org/10.3390/w10050594

Freshwater Health Index. (2025). Freshwater Health Index. https://www.freshwaterhealthindex.org

Fuentes, I., Fuster, R., Avilés, D., & Vervoort, W. (2021). Water scarcity in central Chile: The effect of climate and land cover changes on hydrologic resources. *Hydrological Sciences Journal*, *66*(6), 1028-1044. https://doi.org/10.1080/02626667.2021.1903475

Fuentes-Hernández, P., Barría-Catalán, T., & Flores-Chávez, J. (2024). Estado, ferrocarril y territorio: Las estrategias gubernamentales para la ocupación de La Araucanía a fines del siglo XIX. *Revista Austral de Ciencias Sociales*, (46), Article 46. http://revistas.uach.cl/index.php/racs/article/view/7557

Fuenzalida, H. (1982). A country of extreme climate. *Chile: Essence and Evolution*, 27-35.

Fundación Terram. (2021). *MINUTA RELATIVA A LA MORTALIDAD MASIVA DE SALMONES CAUSADAS POR FLORACIONES ALGALES NOCIVAS (FAN) EN LAS REGIONES DE LOS LAGOS Y AYSÉN*. https://www.terram.cl/descargar/recursos_naturales/salmonicultura/Minuta-Mortalidad-Masiva-de-Salmones-en-Los-Lagos-y-AyseCC81n.pdf

Fustos-Toribio, I., Manque-Roa, N., Vásquez Antipan, D., Hermosilla Sotomayor, M., & Letelier Gonzalez, V. (2022). Rainfall-induced landslide early warning system based on corrected mesoscale numerical models: An application for the southern Andes. *Natural Hazards and Earth System Sciences*, *22*(6), 2169-2183. https://doi.org/10.5194/nhess-22-2169-2022

Galarce, L. C. (2020, julio 3). Protección de los ecosistemas acuáticos ante la presión de la crisis económica que viene. *CIPER Chile*. https://www.ciperchile.cl/2020/07/03/proteccion-de-los-ecosistemas-acuaticos-ante-la-presion-de-la-crisis-economica-que-viene/

Gao, H., Birkett, C., & Lettenmaier, D. P. (2012). Global monitoring of large reservoir storage from satellite remote sensing. *Water Resources Research*, *48*(9). https://doi.org/10.1029/2012WR012063

Gao, Y., Xie, Y., & Zou, D. (2020). Hydrological regime change and its ecological responses in East Dongting Lake, China. *Ecohydrology & Hydrobiology*, *20*(1), 142-150. https://doi.org/10.1016/j.ecohyd.2019.07.003

Garreaud, R. D. (2009). The Andes climate and weather. *Advances in Geosciences*, *22*, 3-11. https://doi.org/10.5194/adgeo-22-3-2009

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., & Veloso-Aguila, D. (2020). The Central Chile Mega Drought (2010–2018): A climate dynamics perspective. *International Journal of Climatology*, *40*(1), 421-439. https://doi.org/10.1002/joc.6219

Garreaud, R. D., Vuille, M., Compagnucci, R., & Marengo, J. (2009). Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology, Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives*, *281*(3), 180-195. https://doi.org/10.1016/j.palaeo.2007.10.032

Gell, P. A., Finlayson, C. M., & Davidson, N. C. (2023). 1—An introduction to the Ramsar Convention on Wetlands. En P. A. Gell, N. C. Davidson, & C. M. Finlayson (Eds.), *Ramsar Wetlands* (pp. 1-36). Elsevier. https://doi.org/10.1016/B978-0-12-817803-4.00018-8

Gerding, V. (2010). *Suelos de humedales y trumaos húmedos del sur de Chile*. http://biblioteca.cehum.org/handle/CEHUM2018/1628

Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. *Sensors*, *16*(8), 1298. https://doi.org/10.3390/s16081298

Gozingan, A. S., Sohou, Z., Baetens, K., Bonou, F., Baloïtcha, E., Gourgue, O., Romanelli, H., Capet, A., & Lacroix, G. (2024). A 3D numerical baroclinic application of the COHERENS model in the Gulf of Guinea, West Africa. *Regional Studies in Marine Science*, *79*, 103811. https://doi.org/10.1016/j.rsma.2024.103811

Granata, F., & Di Nunno, F. (2025). Pathways for Hydrological Resilience: Strategies for Adaptation in a Changing Climate. *Earth Systems and Environment*. https://doi.org/10.1007/s41748-024-00567-x

Gubrium, J. F., Holstein, J. A., Marvasti, A. B., & McKinney, K. D. (2012). *The SAGE Handbook of Interview Research: The Complexity of the Craft*. SAGE Publications.

Gudynas, E. (2014). *Cuando los extractivismos reconPguran democracias y derechos Tensiones y contradicciones bajo el progresismo realmente gobernante*.

Gudynas, E. (2015). *Derechos de la naturaleza: Ética biocéntrica y políticas ambientales*. Editorial Abya-Yala. https://books.google.es/books?hl=es&lr=&id=FONZEAAAQBAJ&oi=fnd&pg=PA5&dq=gudynas+2015+pol%C3%ADticas+ambientales&ots=XWxfwm2CuX&sig=WCdqNCNGMdVkOrztuZc7SztKDPU

Gudynas, E. (2017). Beyond varieties of development: Disputes and alternatives. En *Rising Powers and South-South Cooperation*. Routledge.

Guo, M., Zhuang, Q., Yao, H., Golub, M., Leung, L. R., Pierson, D., & Tan, Z. (2021). Validation and Sensitivity Analysis of a 1-D Lake Model Across Global Lakes.

Journal of Geophysical Research: Atmospheres, *126*(4), e2020JD033417. https://doi.org/10.1029/2020JD033417

Guo, Y., Ren, Z., Dong, Y., Zhang, P., Wang, C., Ma, Z., & He, X. (2023). Multifunctionality can be promoted by increasing agriculture-dominated heterogeneous landscapes in an agro-forestry interlacing zone in northeast China. *Landscape and Urban Planning*, *238*, 104832. https://doi.org/10.1016/j.landurbplan.2023.104832

Hammer, D. A., & Bastian, R. K. (1989). Wetlands Ecosystems: Natural Water Purifiers? En *Constructed Wetlands for Wastewater Treatment*. CRC Press.

Hansen, G. J. A., Wehrly, K. E., Vitense, K., Walsh, J. R., & Jacobson, P. C. (2022). Quantifying the resilience of coldwater lake habitat to climate and land use change to prioritize watershed conservation. *Ecosphere*, *13*(7), e4172. https://doi.org/10.1002/ecs2.4172

Hansen, G., & Stone, D. (2016). Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, *6*(5), 532-537. https://doi.org/10.1038/nclimate2896

Hargrove, A. (2021). The global water crises: A cross-national analysis of metabolic rift theory. *Journal of Political Ecology*, *28*, 2925. https://doi.org/10.2458/jpe.2925

Haustein, K., Allen, M. R., Forster, P. M., Otto, F. E. L., Mitchell, D. M., Matthews, H. D., & Frame, D. J. (2017). A real-time Global Warming Index. *Scientific Reports*, *7*(1), 15417. https://doi.org/10.1038/s41598-017-14828-5

He, C., Malcolm, S. B., Dahlberg, K. A., & Fu, B. (2000). A conceptual framework for integrating hydrological and biological indicators into watershed management. *Landscape and Urban Planning*, *49*(1), 25-34. https://doi.org/10.1016/S0169-2046(00)00047-5

Heilmayr, R., Echeverría, C., Fuentes, R., & Lambin, E. F. (2016). A plantation-dominated forest transition in Chile. *Applied Geography*, *75*, 71-82. https://www.sciencedirect.com/science/article/pii/S0143622816302600

Hernandez, D., Mendoza, P. A., Boisier, J. P., & Ricchetti, F. (2022). Hydrologic Sensitivities and ENSO Variability Across Hydrological Regimes in Central Chile (28°–41°S). *Water Resources Research*, *58*(9), e2021WR031860. https://doi.org/10.1029/2021WR031860

Herod, A. (1993). Gender Issues in the Use of Interviewing as a Research Method∗. *The Professional Geographer*, *45*(3), 305-317. https://doi.org/10.1111/j.0033-0124.1993.00305.x

Hersbach. (2023). *ERA5 hourly data on single levels from 1940 to present*. https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview

Hipsey, M. R., Bruce, L. C., Boon, C., Busch, B., Carey, C. C., Hamilton, D. P., Hanson, P. C., Read, J. S., de Sousa, E., Weber, M., & Winslow, L. A. (2019). A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geoscientific Model Development*, *12*(1), 473-523. https://doi.org/10.5194/gmd-12-473-2019

Hodges, B. R., Imberger, J., & Laval, B. (2000). *Modeling the Hydrodynamics of Stratified Lakes*.

Holling, C. S. (1986). The resilience of terrestrial ecosystems: Local surprise and global change. *Sustainable development of the biosphere*, *14*, 292-317.

Hosseini-Sadabadi, S. A., Rousseau, A. N., Sadeghian, A., Foulon, E., & Behmel, S. (2023). A 3D numerical modeling of the links between hydrodynamics, dissolved oxygen, and water temperature of a northern rural-urban shallow lake with two distinct basins. *Environmental Monitoring and Assessment*, *195*(10), 1198. https://doi.org/10.1007/s10661-023-11744-2

Hou, M., Wei, J., Chu, H., Shi, Y., Ayantobo, O. O., Xu, J., Zhu, X., & Ren, Y. (2022). Conceptual hydrological model-guided SVR approach for monthly lake level reconstruction in the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *44*, 101271. https://doi.org/10.1016/j.ejrh.2022.101271

Hu, S., Niu, Z., & Chen, Y. (2017). Global Wetland Datasets: A Review. *Wetlands*, *37*(5), 807-817. https://doi.org/10.1007/s13157-017-0927-z

Hu, S., Niu, Z., Chen, Y., Li, L., & Zhang, H. (2017). Global wetlands: Potential distribution, wetland loss, and status. *Science of The Total Environment*, *586*, 319-327. https://www.sciencedirect.com/science/article/pii/S0048969717302425

Huang, J., Yu, H., Han, D., Zhang, G., Wei, Y., Huang, J., An, L., Liu, X., & Ren, Y. (2020). Declines in global ecological security under climate change. *Ecological Indicators*, *117*, 106651. https://www.sciencedirect.com/science/article/pii/S1470160X20305884

Huang, L., Wang, J., & Chen, X. (2022). Ecological infrastructure planning of large river basin to promote nature conservation and ecosystem functions. *Journal of Environmental Management*, *306*, 114482. https://www.sciencedirect.com/science/article/pii/S030147972200055X

Huang, L., Woolway, R. I., Timmermann, A., Lee, S.-S., Rodgers, K. B., & Yamaguchi, R. (2024). Emergence of lake conditions that exceed natural temperature variability. *Nature Geoscience*, *17*(8), 763-769. https://doi.org/10.1038/s41561-024-01491-5

Huenupil-Marihuen., M., Garces-Vargas, M., Llevilao-Colil, O., L., A.-P., & Medina-Riquelme, F. (2010). *Historia de Tirúa*.

Huttula, T., & Liukko, N. (2014). *Lake Pyykösjärvi water quality model*.

IDE. (2025). *Infraestructura de datos espaciales. Geoportal de Chile*. https://www.geoportal.cl/catalog

IDE minagri. (2025). *Planificación Catastral | IDE minagri*. https://ide.minagri.gob.cl/geoweb/2019/11/22/planificacion-catastral/

Imberger, J., & Patterson, J. C. (1989). Physical Limnology. En J. W. Hutchinson & T. Y. Wu (Eds.), *Advances in Applied Mechanics* (Vol. 27, pp. 303-475). Elsevier. https://doi.org/10.1016/S0065-2156(08)70199-6

INEa. (2017). *ArcGIS Web Application*. https://ine-chile.maps.arcgis.com/apps/webappviewer/index.html?id=d0bff7af90384faa98d6ff69faa0d6d2

INEb. (2024). *Censo de Población y Vivienda*. Default. http://www.ine.gob.cl/estadisticas/sociales/censos-de-poblacion-y-vivienda/censo-de-poblacion-y-vivienda

INFOR, I. (2014). *Exportaciones forestales chilenas 2013*. INFOR. https://doi.org/10.52904/20.500.12220/20791

Interferencia. (2023, febrero 14). *Ministro de Economía confirma postergación de debate sobre nueva regulación forestal planteada por Boric*. Interferencia. https://interferencia.cl/articulos/ministro-de-economia-confirma-postergacion-de-debate-sobre-nueva-regulacion-forestal

International Lake Environment Committee, I. L. E. C. (2007). Integrated lake basin management: An introduction. *International Lake Environment Committee Foundation. Kusatsu, Japan*, *26*.

International Lake EnvironmentCommitte, I. L. E. (2005). *Managing lakes and their basins for sustainable use: A report for lake basin managers and stakeholders*. International Lake Environment Committee Foundation. https://cir.nii.ac.jp/crid/1971430859734593319

Ishikawa, M., Gonzalez, W., Golyjeswski, O., Sales, G., Rigotti, J. A., Bleninger, T., Mannich, M., & Lorke, A. (2022). Effects of dimensionality on the performance of hydrodynamic models for stratified lakes and reservoirs. *Geoscientific Model Development*, *15*(5), 2197-2220. https://doi.org/10.5194/gmd-15-2197-2022

Iturra Urzúa, J. M. (2024). *Saqueo al humedal de Quilicura. Construcciones sobre el agua*. https://repositorio.uchile.cl/handle/2250/198083

Jacques Coper, M., & Garreaud Salazar, R. (2015). *Characterization of the 1970s climate shift in South America*. https://doi.org/10.1002/joc.4120

Jansen, J., Simpson, G. L., Weyhenmeyer, G. A., Härkönen, L. H., Paterson, A. M., del Giorgio, P. A., & Prairie, Y. T. (2024). Climate-driven deoxygenation of northern lakes. *Nature Climate Change*, *14*(8), 832-838. https://doi.org/10.1038/s41558-024-02058-3

Jerlov. (1968). *Optical Oceanography*. Elsevier.

Ji, L., Senay, G. B., & Verdin, J. P. (2015). *Evaluation of the Global Land Data Assimilation System (GLDAS) Air Temperature Data Products*. https://doi.org/10.1175/JHM-D-14-0230.1

Jian, J., Ryu, D., Costelloe, J. F., & Su, C.-H. (2017). Towards hydrological model calibration using river level measurements. *Journal of Hydrology: Regional Studies*, *10*, 95-109. https://doi.org/10.1016/j.ejrh.2016.12.085

Jiang, Q., Li, W., Fan, Z., He, X., Sun, W., Chen, S., Wen, J., Gao, J., & Wang, J. (2021). Evaluation of the ERA5 reanalysis precipitation dataset over Chinese Mainland. *Journal of Hydrology*, *595*, 125660. https://doi.org/10.1016/j.jhydrol.2020.125660

Jorgensen, S. E., & Rast, W. (2007). The use of models for synthesizing knowledge for integrated lake basin management, and facilitating implementation of the World Lake Vision. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *12*(1), 3-13. https://doi.org/10.1111/j.1440-1770.2007.00316.x

Kanazawa, M. (2023). *Research Methods for Environmental Studies: A Social Science Approach* (2.ª ed.). Routledge. https://doi.org/10.4324/9781003261117

Kay, J. J., & Schneider, E. (1995). Embracing Complexity the Challenge of the Ecosystem Approach. En L. Westra & J. Lemons (Eds.), *Perspectives on Ecological Integrity* (pp. 49-59). Springer Netherlands. https://doi.org/10.1007/978-94-011-0451-7_4

Kaya, Y. (2025). Evaluation of ICESat-2 Laser Altimetry for Inland Water Level Monitoring: A Case Study of Canadian Lakes. *Water*, *17*(7), 1098. https://doi.org/10.3390/w17071098

Kaya, Y., Balik Sanli, F., & Abdikan, S. (2025). Refinement of ICESat-2 derived inland water surface levels with the TG20 local geoid model: In the case of Türkiye

lakes. *Physics and Chemistry of the Earth, Parts A/B/C*, *139*, 103900. https://doi.org/10.1016/j.pce.2025.103900

King, A. W. (1993). Considerations of Scale and Hierarchy. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Kirby, R. R., Beaugrand, G., Kleparski, L., Goodall, S., & Lavender, S. (2021). Citizens and scientists collect comparable oceanographic data: Measurements of ocean transparency from the Secchi Disk study and science programmes. *Scientific Reports*, *11*(1), 15499. https://doi.org/10.1038/s41598-021-95029-z

KNMI. (2024). *KNMI Climate explorer*. https://climexp.knmi.nl/selectindex.cgi?id=someone@somewhere

Kondo, J. (1975). Air-sea bulk transfer coefficients in diabatic conditions. *Boundary-Layer Meteorology*, *9*(1), 91-112. https://doi.org/10.1007/BF00232256

Korkou, M., Tarigan, A. K. M., & Hanslin, H. M. (2023). The multifunctionality concept in urban green infrastructure planning: A systematic literature review. *Urban Forestry & Urban Greening*, *85*, 127975. https://doi.org/10.1016/j.ufug.2023.127975

Kornijów, R. (2023). Lake aging concept revisited: Alternative comprehensive approach to lake ontogeny. *Canadian Journal of Fisheries and Aquatic Sciences*, *80*(8), 1385-1393. https://doi.org/10.1139/cjfas-2023-0027

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259-263. https://doi.org/10.1127/0941-2948/2006/0130

Kreakie, B. J., Shivers, S. D., Hollister, J. W., & Milstead, W. B. (2021). Predictive Model of Lake Photic Zone Temperature Across the Conterminous United States. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.707874

Kumar, L., & Mutanga, O. (2018). Google Earth Engine Applications Since Inception: Usage, Trends, and Potential. *Remote Sensing*, *10*(10), Article 10. https://doi.org/10.3390/rs10101509

Kwak, T. J., & Freeman, M. (2010). *Assessment and management of ecological integrity: Chapter 12*. 353-394. https://pubs.usgs.gov/publication/70154946

Labraña-Muñoz, C., & Arcas-Morales, G. (2006). San Pedro de la Paz: Del Fuerte a la comuna (1604-2001). *Hualpén, Chile: Impresos Andalién, Ilustre Municipalidad de San Pedro de la Paz*.

Lara, A., Jones, J., Little, C., & Vergara, N. (2021). Streamflow response to native forest restoration in former Eucalyptus plantations in south central Chile. *Hydrological Processes*, *35*(8), e14270. https://doi.org/10.1002/hyp.14270

Lara, A., Solari, M. E., Prieto, M. D. R., & Peña, M. P. (2012). Reconstrucción de la cobertura de la vegetación y uso del suelo hacia 1550 y sus cambios a 2007 en la ecorregión de los bosques valdivianos lluviosos de Chile (35º—43º 30´ S). *Bosque (Valdivia)*, *33*(1), 13-23. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-92002012000100002&lng=es&nrm=iso&tlng=en

Lee, J.-W., Park, S.-R., & Lee, S.-W. (2023). Effect of Land Use on Stream Water Quality and Biological Conditions in Multi-Scale Watersheds. *Water*, *15*(24), 4210. https://doi.org/10.3390/w15244210

Lee, K., Nam, S., Cho, Y.-K., Jeong, K.-Y., & Byun, D.-S. (2022). Determination of Long-Term (1993–2019) Sea Level Rise Trends Around the Korean Peninsula

Using Ocean Tide-Corrected, Multi-Mission Satellite Altimetry Data. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.810549

Lewis, S. L., & Maslin, M. A. (2015). Defining the Anthropocene. *Nature*, *519*(7542), 171-180. https://www.nature.com/articles/nature14258

Lieberherr, G., & Wunderle, S. (2018). Lake Surface Water Temperature Derived from 35 Years of AVHRR Sensor Data for European Lakes. *Remote Sensing*, *10*(7), Article 7. https://doi.org/10.3390/rs10070990

Lin, S., Boegman, L., Shan, S., & Mulligan, R. (2022). An automatic lake-model application using near-real-time data forcing: Development of an operational forecast workflow (COASTLINES) for Lake Erie. *Geoscientific Model Development*, *15*(3), 1331-1353. https://doi.org/10.5194/gmd-15-1331-2022

Little, C., Lara, A., McPhee, J., & Urrutia, R. (2009). Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile. *Journal of Hydrology*, *374*(1), 162-170. https://doi.org/10.1016/j.jhydrol.2009.06.011

Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., Valenzuela, R. A., Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., & Valenzuela, R. A. (2017). La agricultura y la élite agraria chilena a través de los catastros agrícolas, c. 1830-1855. *Historia (Santiago)*, *50*(2), 597-639. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-71942017000200597&lng=es&nrm=iso&tlng=es

Long, L. (2017, marzo 1). The Stages of Lake and Pond Succession. *SOLitude Lake Management: Full-Service Lake And Pond Management*. https://www.solitudelakemanagement.com/the-stages-of-lake-and-pond-succession/

Lovell, S. T. (2010). Multifunctional Urban Agriculture for Sustainable Land Use Planning in the United States. *Sustainability*, *2*(8), 2499-2522. https://doi.org/10.3390/su2082499

Luo, J., Duan, H., Xu, Y., Shen, M., Zhang, Y., Xiao, Q., Ni, G., Wang, K., Xin, Y., Qi, T., Feng, L., Qiu, Y., Jeppesen, E., & Woolway, R. I. (2025). Global trends and regime state shifts of lacustrine aquatic vegetation. *The Innovation*, *6*(3), 100784. https://doi.org/10.1016/j.xinn.2024.100784

Luyten, P. (2025). *COHERENS: A Coupled Hydrodynamical Ecological Model for Regional and Shelf Seas: User Documentation (Version 3)*. Operational Directorate Natural Environment, Royal Belgian Institute of Natural Sciences. https://doi.org/10.5281/zenodo.11261106.

Lyche Solheim, A., Globevnik, L., Austnes, K., Kristensen, P., Moe, S. J., Persson, J., Phillips, G., Poikane, S., van de Bund, W., & Birk, S. (2019). A new broad typology for rivers and lakes in Europe: Development and application for large-scale environmental assessments. *Science of The Total Environment*, *697*, 134043. https://doi.org/10.1016/j.scitotenv.2019.134043

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J. B., Jena, J., Bhattacharya, U., Duvvada, S. K., Lalichetti, S., & Sairam, M. (2021). Intercropping—A Low Input Agricultural Strategy for Food and Environmental Security. *Agronomy*, *11*(2), Article 2. https://www.mdpi.com/2073-4395/11/2/343

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015a). Validation of the AquaCrop model for irrigated rice production under

varied water regimes in Bangladesh. *Agricultural Water Management*, *159*, 331-340. https://doi.org/10.1016/j.agwat.2015.06.022

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015b). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*(C), 331-340. https://ideas.repec.org//a/eee/agiwat/v159y2015icp331-340.html

Mano, A., Malve, O., Koponen, S., Kallio, K., Taskinen, A., Ropponen, J., Juntunen, J., & Liukko, N. (2015). Assimilation of satellite data to 3D hydrodynamic model of Lake Säkylän Pyhäjärvi. *Water Science and Technology*, *71*(7), 1033-1039. https://doi.org/10.2166/wst.2015.042

Mano, A., & Shuku, T. (2014). *Application of the Particle Filter to COHERENS V2 model of Lake Säkylän Pyhäjärvi*.

Manuschevich, D. (2016). Neoliberalization of forestry discourses in Chile. *Forest Policy and Economics*, *69*, 21-30. https://doi.org/10.1016/j.forpol.2016.03.006

Marinov, D., Norro, A., & Zaldívar, J.-M. (2006). Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore). *Ecological Modelling, Special Issue on Southern European Coastal Lagoons*, *193*(1), 52-68. https://doi.org/10.1016/j.ecolmodel.2005.07.042

Martínez Retureta, R. (2021). *Efectos del cambio de uso cobertura del suelo sobre la respuesta hidrológica en cuencas del centro sur de Chile bajo escenarios de cambio climático.* https://repositorio.udec.cl/handle/11594/6538

Martínez-Fernández, J., Banos-González, I., & Esteve-Selma, M. Á. (2021). An integral approach to address socio-ecological systems sustainability and their uncertainties. *Science of The Total Environment*, *762*, 144457. https://www.sciencedirect.com/science/article/pii/S0048969720379882

Martínez-Tilleria, K., Núñez-Ávila, M., León, C. A., Pliscoff, P., Squeo, F. A., & Armesto, J. J. (2017). A framework for the classification Chilean terrestrial ecosystems as a tool for achieving global conservation targets. *Biodiversity and Conservation*, *26*(12), 2857-2876. https://doi.org/10.1007/s10531-017-1393-x

Marttunen, M., Hellsten, S., Glover, B., Tarvainen, A., Klintwall, L., Olsson, H., & Pedersen, T. S. (2006). Heavily regulated lakes and the European Water framework directive—Comparisons from Finland, Norway, Sweden, Scotland and Austria. *E-Water*, *5*, 1-22. https://www.ewa-online.eu/files/downloads/publications/E-Water_Journal/42_2006_05.pdf

Mason, I. M., Guzkowska, M. A. J., Rapley, C. G., & Street-Perrott, F. A. (1994). The response of lake levels and areas to climatic change. *Climatic Change*, *27*(2), 161-197. https://doi.org/10.1007/BF01093590

Mayer, A. L., & Rietkerk, M. (2004). The Dynamic Regime Concept for Ecosystem Management and Restoration. *BioScience*, *54*(11), 1013-1020. https://doi.org/10.1641/0006-3568(2004)054[1013:TDRCFE]2.0.CO;2

McDougall, T. J., Jackett, D. R., Wright, D. G., & Feistel, R. (2003). *Accurate and Computationally Efficient Algorithms for Potential Temperature and Density of Seawater*. https://journals.ametsoc.org/view/journals/atot/20/5/1520-0426_2003_20_730_aaceaf_2_0_co_2.xml

McGregor, G. (2017). Hydroclimatology, modes of climatic variability and stream flow, lake and groundwater level variability: A progress report. *Progress in Physical*

Geography: Earth and Environment, *41*(4), 496-512. https://doi.org/10.1177/0309133317726537

Meerhoff, M., Audet, J., Davidson, T. A., De Meester, L., Hilt, S., Kosten, S., Liu, Z., Mazzeo, N., Paerl, H., Scheffer, M., & Jeppesen, E. (2022). Feedback between climate change and eutrophication: Revisiting the allied attack concept and how to strike back. *Inland Waters*, *12*(2), 187-204. https://doi.org/10.1080/20442041.2022.2029317

Mellor, G. L. (1988). *A THREE-DIMENSIONAL, PRIMITIVE EQUATION, NUMERICAL OCEAN MODEL*.

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016a). Trophic State Index estimation from remote sensing of lake Chapala, México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016b). Trophic State Index estimation from remote sensing of lake Chapala, México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Meng, B., Liu, J., Bao, K., & Sun, B. (2020). Methodologies and Management Framework for Restoration of Wetland Hydrologic Connectivity: A Synthesis. *Integrated Environmental Assessment and Management*, *16*(4), 438-451. https://doi.org/10.1002/ieam.4256

Merryfield, W. J., & Lee, W.-S. (2023). Estimating Probabilities of Extreme ENSO Events from Copernicus Seasonal Hindcasts. *Asia-Pacific Journal of Atmospheric Sciences*, *59*(4), 479-493. https://doi.org/10.1007/s13143-023-00328-2

Metcalfe, A. N., Kennedy, T. A., Mendez, G. A., & Muehlbauer, J. D. (2022). Applied citizen science in freshwater research. *WIREs Water*, *9*(2), e1578. https://doi.org/10.1002/wat2.1578

Mironov, D., Golosov, S., Heise, E., Kourzeneva, E., Ritter, B., Schneider, N., & Terzhevik, A. (2005). FLake – A Lake Model for Environmental Applications. *2005*.

Mitra, S., Wassmann, R., & Vlek, P. L. G. (2003). *Global inventory of wetlands and their role in the carbon cycle* (ZEF - Discussion Papers on Development Policy No. 64). https://doi.org/10.22004/ag.econ.18771

MMA. (2020). *ANTEPROYECTO DEL PLAN DE DESCONTAMINACION POR CLOROFILA "A", TliANSPARENCIA Y FOSFORO DISUELTO, PARA LA CUENCA DEL LAGO VILLARRICA.* https://consultaindigena.mma.gob.cl/wp-content/uploads/2021/11/Anteproyecto-PDA-Lago-Villarrica.pdf

Montecinos, A., & Aceituno, P. (2003). *Seasonality of the ENSO-Related Rainfall Variability in Central Chile and Associated Circulation Anomalies*. https://journals.ametsoc.org/view/journals/clim/16/2/1520-0442_2003_016_0281_soterr_2.0.co_2.xml

Morales-Magaña, M., Paneque-Galvez, J., Torres-Abreu, A., Mori-González, R., Reyes Díaz, A. M., Rivera Ramos, J. C., Molina Carrasquillo, R., & Molina Parrilla, S. C. (2020). *Community experiences in water management: Social innovation, participatory science, and dialogue of knowledges II (in Portuguese and Spanish)*. https://doi.org/10.5281/zenodo.4362629

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, *50*(3), 885-900. https://doi.org/10.13031/2013.23153

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). *Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria*.

Mortimer, C. H. (1974). Lake hydrodynamics. *Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Mitteilungen*. (world). https://www.tandfonline.com/doi/abs/10.1080/05384680.1974.11923886

Mukaka, M. M. (2012). A guide to appropriate use of Correlation coefficient in medical research. *Malawi Medical Journal*, *24*(3), 69-71. https://www.ajol.info/index.php/mmj/article/view/81576

Muñoz Aguayo, P. (2013). *Apuntes de teledetección: Índices de vegetación.* https://bibliotecadigital.ciren.cl/bitstreams/af8fd625-0d58-4941-8530-7186a6b3d93e/download

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349-4383. https://doi.org/10.5194/essd-13-4349-2021

Naciones Unidas, M. J. (2025). Objetivos y metas de desarrollo sostenible. *Desarrollo Sostenible*. https://www.un.org/sustainabledevelopment/es/objetivos-de-desarrollo-sostenible/

NASA. (2025). *ASF Data Search*. https://search.asf.alaska.edu/

NASA SWOT. (2024). *NASA SWOT. Jet Propulsion Laboratory: Surface Water and Ocean Topography (SWOT).* https://swot.jpl.nasa.gov/

National Institute of Water and Atmospheric Research. (2025). *Lakespi (Lake Submerged Plant Indicators)*. https://lakespi.niwa.co.nz/

Ndehedehe, C. E., Awange, J. L., Kuhn, M., Agutu, N. O., & Fukuda, Y. (2017). Analysis of hydrological variability over the Volta river basin using in-situ data and satellite observations. *Journal of Hydrology: Regional Studies*, *12*, 88-110. https://doi.org/10.1016/j.ejrh.2017.04.005

Nekouee, N., Hamidi, S. A., Roberts, P. J. W., & Schwab, D. J. (2015). Assessment of a 3D Hydrostatic Model (POM) in the Near Field of a Buoyant River Plume in Lake Michigan. *Water, Air, & Soil Pollution*, *226*(7), 210. https://doi.org/10.1007/s11270-015-2488-1

Ngamile, S., Madonsela, S., & Kganyago, M. (2025). Trends in remote sensing of water quality parameters in inland water bodies: A systematic review. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1549301

Nhamo, L., Magidi, J., & Dickens, C. (2017). Determining wetland spatial extent and seasonal variations of the inundated area using multispectral remote sensing. *Water SA*, *43*(4), 543-552. https://doi.org/10.4314/wsa.v43i4.02

Nielsen, L. (2020, enero). *(PDF) Toward a unified theory of risk, resilience and sustainability science with applications for education and governance*. https://www.researchgate.net/publication/348407042_Toward_a_unified_theory_of_risk_resilience_and_sustainability_science_with_applications_for_education_and_governance

NOAA. (2024a). *El Niño / Southern Oscillation (ENSO) | Equatorial Pacific Sea Surface Temperatures (SST) | National Centers for Environmental Information (NCEI)*. https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024b). *National Oceanic and Atmospheric Administration (NOAA). Antartic Oscillation.* https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml

NOAA. (2024c). *National Oceanic and Atmospheric Administration (NOAA). Equatorial Pacific Sea Surface Temperatures (SST).* https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024d). *National Oceanic and Atmospheric Administration (NOAA). Pacific Decadal Oscillation (PDO).* https://www.ncei.noaa.gov/access/monitoring/pdo/

Odeku, K. O. (2022). Climate injustices due to the unequal and disproportionate impacts of climate change. *Perspectives of Law and Public Administration*, *11*(1), 103-110. https://www.ceeol.com/search/article-detail?id=1102605

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., & Calvez, R. (2018). Surface water monitoring in small water bodies: Potential and limits of multi-sensor Landsat time series. *Hydrology and Earth System Sciences*, *22*(8), 4349-4380. https://doi.org/10.5194/hess-22-4349-2018

Olvera, M. J. T. (2018). *Integridad ecológica como una herramienta de evaluación en cuencas hidrográficas. Caso de estudio Microcuenca del Río Jalpan*. https://ring.uaq.mx/handle/123456789/1004

Onyutha, C. (2021). A hydrological model skill score and revised R-squared. *Hydrology Research*, *53*(1), 51-64. https://doi.org/10.2166/nh.2021.071

Oppliger, A. (2015). *Atlas del Agua – Chile 2016 / Atlas of Water—Chile 2016*. Ministry of Public Works - General Direction of Waters of Chile. https://iris.unil.ch/handle/iris/49995

O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J. D., McIntyre, P. B., Kraemer, B. M., Weyhenmeyer, G. A., Straile, D., Dong, B., Adrian, R., Allan, M. G., Anneville, O., Arvola, L., Austin, J., Bailey, J. L., … Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, *42*(24), 10,773-10,781. https://doi.org/10.1002/2015GL066235

Organización del Tratado de Cooperación Amazónica. (2025). *Proyecto Cuenca Amazónica. Implementación del Programa de Acciones Estratégicas en la Cuenca del río Amazonas considerando la Variabilidad y el Cambio Climático.* https://aguasamazonicas.otca.org/monitoreo-ambiental-y-de-los-recursos-hidricos/sistema-integrado-de-monitoreo-de-los-recursos-hidricos/

Ortiz, A. M. D., Gayó, E. M., Henríquez, N. C., Henríquez, B. J., & Pauchard, A. (2024). Exploring the multifunctional landscapes model in areas dominated by non-native tree plantations. *Trees, Forests and People*, *17*, 100617. https://www.sciencedirect.com/science/article/pii/S2666719324001249

Otavo, S., & Echeverría, C. (2017). Fragmentación progresiva y pérdida de hábitat de bosques naturales en uno de los hotspot mundiales de biodiversidad. *Revista Mexicana de Biodiversidad*, *88*(4), 924-935. https://doi.org/10.1016/j.rmb.2017.10.041

Otero Durán, L. (2012). La huella del fuego: Historia de los bosques nativos poblamiento y cambios en el paisaje de lsur de Chile. *2012*. https://www.sidalc.net/search/Record/KOHA-OAI-FCF:15776/Description

Oxley, R. L. (2015). *Ecological, environmental and hydrological integrity in sustainable water resource management for river basins*. Arizona State University. https://search.proquest.com/openview/4d57cce5b508c9900cd2f564fdc817bd/1?pq-origsite=gscholar&cbl=18750

Palomo, I., Locatelli, B., Otero, I., Colloff, M., Crouzat, E., Cuni-Sanchez, A., Gómez-Baggethun, E., González-García, A., Grêt-Regamey, A., Jiménez-Aceituno, A., Martín-López, B., Pascual, U., Zafra-Calvo, N., Bruley, E., Fischborn, M., Metz, R., & Lavorel, S. (2021). Assessing nature-based solutions for transformative change. *One Earth*, *4*(5), 730-741. https://doi.org/10.1016/j.oneear.2021.04.013

Paredes, M. L., & Ulloa, M. E. (2021). Implementación de los ECMPO y las disputas por el control del territorio: El caso del ECMPO Mañihueico-Huinay y los mitilicultores de la comuna de Hualaihué, Región de Los Lagos. *Revista LIDER*, 62-87. https://revistas.ulagos.cl/index.php/index

Pareeth, S., Salmaso, N., Adrian, R., & Neteler, M. (2016). Homogenised daily lake surface water temperature data generated from multiple satellite sensors: A long-term case study of a large sub-Alpine lake. *Scientific Reports*, *6*(1), 31251. https://doi.org/10.1038/srep31251

Parra et al. (2016). *Una aproximación interdisciplinaria al estudio... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Una+aproximaci%C3%B3n+interdisciplinaria+al+estudio+de+floraciones+de+algas+nocivas+en+Lagos+Urbanos+En+Chile&author=Parra,+O.&author=Baeza,+C.&author=Almanza,+V.&author=Urrutia,+R.&author=Figueroa,+R.&author=Fern%C3%A1ndez,+X.&author=de+Or%C3%BAe,+P.&author=Gonz%C3%A1lez,+P.&author=Beltr%C3%A1n,+J.&author=Becerra,+J.&publication_year=2016&pages=133%E2%80%93146

Parra et al., O. (2003). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*, 51-83. https://ui.adsabs.harvard.edu/abs/2003Limne..22...51P

Parra, O. (2003a). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://doi.org/10.23818/limn.22.04

Parra, O. (2003b). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://www.limnetica.net/documentos/limnetica/limnetica-22-1-p-51.pdf

Parra, O., Basualto, S., Urrutia, R., & Valdovinos, C. (1999). Estudio comparativo de la diversidad fitoplanctónica de cinco lagos de diferentes niveles de eutroficación del área litoral de la región del Biobio (Chile). *Gayana Botánica (Chile)*, *56*, 93-108.

Parra, O. O. (1989). *La eutroficación de la Laguna Grande de San Pedro, Concepción, Chile: Un caso de estudio.*

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005a). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005b). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Pedreros-Guarda, M. (2025). *Github COHERENS Lake*. https://github.com/mpedreros/COHERENS_Lake.git

Pedreros-Guarda, M. (2025). *Mpedreros/TesisDoctoral* [Software]. https://github.com/mpedreros/TesisDoctoral (Obra original publicada en 2025)

Pedreros-Guarda, M., Abarca-del-Río, R., Crétaux, J. F., & Paris, A. (2025). Long-term lake water levels in central Chile using satellite altimetry and conceptual hydrological modelling approaches. *Advances in Space Research*, *76*(4), 1997-2018. https://doi.org/10.1016/j.asr.2025.05.091

Pedreros-Guarda, M., Abarca-del-Río, R., Escalona, K., García, I., & Parra, Ó. (2021). A Google Earth Engine Application to Retrieve Long-Term Surface Temperature for Small Lakes. Case: San Pedro Lagoons, Chile. *Remote Sensing*, *13*(22), 4544. https://doi.org/10.3390/rs13224544

Piccioni, F., Casenave, C., Lemaire, B. J., Le Moigne, P., Dubois, P., & Vinçon-Leite, B. (2021). The thermal response of small and shallow lakes to climate change: New insights from 3D hindcast modelling. *Earth System Dynamics*, *12*(2), 439-456. https://doi.org/10.5194/esd-12-439-2021

Piccolroaz, S., Toffolon, M., & Majone, B. (2013). A simple lumped model to convert air temperature into surface water temperature in lakes. *Hydrology and Earth System Sciences*, *17*(8), 3323-3338. https://doi.org/10.5194/hess-17-3323-2013

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024a). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024b). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Pilla, R. M., Williamson, C. E., Zhang, J., Smyth, R. L., Lenters, J. D., Brentrup, J. A., Knoll, L. B., & Fisher, T. J. (2018). Browning-Related Decreases in Water Transparency Lead to Long-Term Increases in Surface Water Temperature and Thermal Stratification in Two Small Lakes. *Journal of Geophysical Research: Biogeosciences*, *123*(5), 1651-1665. https://doi.org/10.1029/2017JG004321

Pinto, A. P., García, P. B., Almonacid, L. E., & Henríquez, B. J. (2023). Zonas de Sacrificio y Recuperación Socioambiental en Chile: Fallas y oportunidades de la política ambiental. *Ambiente & Sociedade*, *26*, e01371. https://www.scielo.br/j/asoc/a/JdDjvNrLpBJPKwYfppfDBWB/

Prats, J., Reynaud, N., Rebière, D., Peroux, T., Tormos, T., & Danis, P.-A. (2018). LakeSST: Lake Skin Surface Temperature in French inland water bodies for

1999–2016 from Landsat archives. *Earth System Science Data*, *10*(2), 727-743. https://doi.org/10.5194/essd-10-727-2018

Qiao, B., Du, T., Ju, J., & Zhu, L. (2025). Water depth inversion based on ICESat-2 and Sentinel-2—A case study of Qiagui Co and Ayakekumu Lake on the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *59*, 102354. https://doi.org/10.1016/j.ejrh.2025.102354

Quevedo, F., Rojas Hernández, J., & Barra, R. O. (2022). Towards a Chilean Water Governance: A Study on the Los Batros and Paicaví Wetland Reservoirs. *Water*, *14*(18), Article 18. https://www.mdpi.com/2073-4441/14/18/2861

Quintana, J. M., & Aceituno, P. (2012). Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30-43º S. *Atmósfera*, *25*(1), 1-22. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S0187-62362012000100001&lng=es&nrm=iso&tlng=en

Randrianiaina, Rakotonirina, Ratiarimanana, & Lahatra. (2018). *Temperature Retrieval of Lake Itasy Using Remote Sensing*. https://scholar.google.com/scholar_lookup?title=Temperature+Retrieval+of+Lake+Itasy+Using+Remote+Sensing&author=Randrianiaina,+J.&author=Rakotonirina,+I.&author=Ratiarimanana,+R.&author=Lahatra,+F.&publication_year=2018&journal=Resour.+Environ.&volume=8&pages=241%E2%80%93244

Regier, H. A. (1993a). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Regier, H. A. (1993b). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Renting, H., Rossing, W. A. H., Groot, J. C. J., Van der Ploeg, J. D., Laurent, C., Perraud, D., Stobbelaar, D. J., & Van Ittersum, M. K. (2009). Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. *Journal of Environmental Management, Multifunctional agriculture - From farm diagnosis to farm design and institutional innovation*, *90*, S112-S123. https://doi.org/10.1016/j.jenvman.2008.11.014

Restrepo, L. A. V., & Sal, A. G. (2008). Un marco conceptual y analítico para estimar la integridad ecológica a escala de paisaje. *Arbor*, *184*(729), Article 729. https://arbor.revistas.csic.es/index.php/arbor/article/view/159

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Roche, P. K., & Campagne, C. S. (2017). From ecosystem integrity to ecosystem condition: A continuity of concepts supporting different aspects of ecosystem sustainability. *Current Opinion in Environmental Sustainability*, *29*, 63-68. https://www.sciencedirect.com/science/article/pii/S1877343517302828

Rockström, J., Donges, J. F., Fetzer, I., Martin, M. A., Wang-Erlandsson, L., & Richardson, K. (2024). Planetary Boundaries guide humanity's future on Earth. *Nature Reviews Earth & Environment*, *5*(11), 773-788. https://www.nature.com/articles/s43017-024-00597-z

Rojas Quezada, C. A., Muñiz Olivera, I., & García-López, M. Á. (2009). Estructura urbana y policentrismo en el Área Metropolitana de Concepción. *EURE (Santiago)*, *35*(105), 47-70. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0250-71612009000200003&lng=es&nrm=iso&tlng=es

Rutllant, J., & Fuenzalida, H. (1991). Synoptic aspects of the central chile rainfall variability associated with the southern oscillation. *International Journal of Climatology*, *11*(1), 63-76. https://doi.org/10.1002/joc.3370110105

Salazar, Á., Thatcher, M., Goubanova, K., Bernal, P., Gutiérrez, J., & Squeo, F. (2024). CMIP6 precipitation and temperature projections for Chile. *Climate Dynamics*, *62*(3), 2475-2498. https://doi.org/10.1007/s00382-023-07034-9

Saloranta, T. M., & Andersen, T. (2007). MyLake—A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations. *Ecological Modelling, Uncertainty in Ecological Models*, *207*(1), 45-60. https://doi.org/10.1016/j.ecolmodel.2007.03.018

San Llorente Capdevila, A., Kokimova, A., Sinha Ray, S., Avellán, T., Kim, J., & Kirschke, S. (2020). Success factors for citizen science projects in water quality monitoring. *Science of The Total Environment*, *728*, 137843. https://doi.org/10.1016/j.scitotenv.2020.137843

Saraceni, M., Brunone, B., Silvestri, L., Meniconi, S., & Cerlini, P. B. (2025). *A Water Mass Balance–Based Procedure Using ERA5 Land Reanalysis and Level Observation to Reconstruct the Past Level Changes of Closed Lakes toward Future Management*. https://doi.org/10.1175/JHM-D-24-0019.1

Sarkar, D., Kar, S. K., Chattopadhyay, A., Shikha, Rakshit, A., Tripathi, V. K., Dubey, P. K., & Abhilash, P. C. (2020). Low input sustainable agriculture: A viable climate-smart option for boosting food production in a warming world. *Ecological Indicators*, *115*, 106412. https://www.sciencedirect.com/science/article/pii/S1470160X20303496

Sarkar, S., & Maity, R. (2021). Global climate shift in 1970s causes a significant worldwide increase in precipitation extremes. *Scientific Reports*, *11*(1), 11574. https://doi.org/10.1038/s41598-021-90854-8

Sarricolea, P., Herrera-Ossandon, M., & Meseguer-Ruiz, Ó. (2017). Climatic regionalisation of continental Chile. *Journal of Maps*, *13*(2), 66-73. https://doi.org/10.1080/17445647.2016.1259592

Sazib, N., Mladenova, I., & Bolten, J. (2018). Leveraging the Google Earth Engine for Drought Assessment Using Global Soil Moisture Data. *Remote Sensing*, *10*(8), Article 8. https://doi.org/10.3390/rs10081265

Schallenberg, M., de Winton, M. D., & Kelly, D. J. (2018). Indicators of Ecological Integrity. En D. P. Hamilton, K. J. Collier, J. M. Quinn, & C. Howard-Williams (Eds.), *Lake Restoration Handbook: A New Zealand Perspective* (pp. 367-393). Springer International Publishing. https://doi.org/10.1007/978-3-319-93043-5_11

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591-596. https://doi.org/10.1038/35098000

Schmid, M., & Read, J. (2022). Heat budget of lakes. En *Encyclopedia of inland waters* (Vol. 1, pp. 467-473). https://doi.org/10.1016/b978-0-12-819166-8.00011-6

Schmithuesen, F. (2007). Multifunctional forestry practices as a land use strategy to meet increasing private and public demands in modern societies. *Journal of Forest Science - UZPI (Czech Republic)*, *53*(6). https://agris.fao.org/search/en/providers/122644/records/647247a2e17b74d2224f615d

Schott, F. A., Wang, W., & Stammer, D. (2007). Variability of Pacific subtropical cells in the 50-year ECCO assimilation. *Geophysical Research Letters*, *34*(5). https://doi.org/10.1029/2006GL028478

Schwatke, C., Dettmering, D., Bosch, W., & Seitz, F. (2015). DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrology and Earth System Sciences*, *19*(10), 4345-4364. https://doi.org/10.5194/hess-19-4345-2015

Seidl, R., & Barthel, R. (2017). Linking scientific disciplines: Hydrology and social sciences. *Journal of Hydrology*, *550*, 441-452. https://doi.org/10.1016/j.jhydrol.2017.05.008

Shao, G. P., & Bishop, I. J. (2025). Citizen science in river monitoring: A systematic literature review of the whys and hows. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1609084

Shchepetkin, A. F., & McWilliams, J. C. (2003). A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. *Journal of Geophysical Research: Oceans*, *108*(C3). https://doi.org/10.1029/2001JC001047

Shine, K. P. (1984). Parametrization of the shortwave flux over high albedo surfaces as a function of cloud thickness and surface albedo. *Quarterly Journal of the Royal Meteorological Society*, *110*(465), 747-764. https://doi.org/10.1002/qj.49711046511

Simon, D. F., Munoz, G., Dinh, Q. T., Duy, S. V., Kavanagh, K., Smith, R., Husk, B., & Sauvé, S. (2023). Adopt a Lake: Successfully Tracking Harmful Cyanobacterial Blooms in Canadian Surface Waters Through Citizen Science. *Citizen Science: Theory and Practice*, *8*(1). https://doi.org/10.5334/cstp.655

Smagorinsky, J. (1963). *GENERAL CIRCULATION EXPERIMENTS WITH THE PRIMITIVE EQUATIONS*. https://journals.ametsoc.org/view/journals/mwre/91/3/1520-0493_1963_091_0099_gcewtp_2_3_co_2.xml

Smith, L. T. (2016). *A descolonizar las metodologías. Investigación y pueblos indígenas: A descolonizar las metodologías. Investigación y pueblos indígenas*. LOM Ediciones.

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, *10*(2), 126-139. https://doi.org/10.1065/espr2002.12.142

Sobarzo, M. B., Figueroa, D., & Arcos, D. R. (1997). The Influence of Winds and Tides in the Formation of Circulation Layers in a Bay, a Case Study: Concepción Bay, Chile. *Estuarine, Coastal and Shelf Science*, *45*(6), 729-736. https://doi.org/10.1006/ecss.1997.0233

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. *Anthropocene Review*, *2*(1), 81-98. http://www.scopus.com/inward/record.url?scp=84996501052&partnerID=8YFLogxK

Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., & Mironov, D. (2010). First steps of a lake model intercomparison project: LakeMIP. *Boreal environment research*, *15*(2), 191. https://search.proquest.com/openview/d60a3674e3599840e062b6afc6aff527/1?pq-origsite=gscholar&cbl=5500736

Suazo, B. (2014). Fragmentación socioespacial en el barrio Boca Sur, San Pedro de la Paz: La necesidad de implementar una planificación participativa. *Universidad de Concepción*.

Sullivan, C. J., Read, J. S., & Hansen, G. J. A. (2025). Climate-driven alterations of lake thermal regimes. *Limnology and Oceanography*, *70*(8), 2348-2364. https://doi.org/10.1002/lno.70128

Sultana, F. (2022). Critical climate justice. *The Geographical Journal*, *188*(1), 118-124. https://onlinelibrary.wiley.com/doi/abs/10.1111/geoj.12417

Szesztay, K. (1974). Water balance and water level fluctuations of lakes. *Hydrological Sciences Bulletin*, *19*(1), 73-84. http://www.tandfonline.com/doi/abs/10.1080/02626667409493872

Tachikawa, T., Hato, M., Kaku, M., & Iwasaki, A. (2011). Characteristics of ASTER GDEM version 2. *2011 IEEE International Geoscience and Remote Sensing Symposium*, 3657-3660. https://doi.org/10.1109/IGARSS.2011.6050017

Taghizadeh, E., Ahmadi-Givi, F., Brocca, L., & Sharifi, E. (2021). Evaluation of satellite/reanalysis precipitation products over Iran. *International Journal of Remote Sensing*, *42*(9), 3474-3497. https://doi.org/10.1080/01431161.2021.1875508

Tavares, M. H., Cunha, A. H. F., Motta-Marques, D., Ruhoff, A. L., Cavalcanti, J. R., Fragoso, C. R., Martín Bravo, J., Munar, A. M., Fan, F. M., & Rodrigues, L. H. R. (2019). Comparison of Methods to Estimate Lake-Surface-Water Temperature Using Landsat 7 ETM+ and MODIS Imagery: Case Study of a Large Shallow Subtropical Lake in Southern Brazil. *Water*, *11*(1), Article 1. https://doi.org/10.3390/w11010168

Tedesco, A. M., López-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Pérez-Hämmerle, K.-V., Brancalion, P. H. S., Wilson, K. A., Oliveira, M., Correa, D. F., Ota, L., Morrison, T. H., Possingham, H. P., Mills, M., Santos, F. C., & Dean, A. J. (2023). Beyond ecology: Ecosystem restoration as a process for social-ecological transformation. *Trends in Ecology & Evolution*, *38*(7), 643-653. https://doi.org/10.1016/j.tree.2023.02.007

Tierney, G. L., Faber-Langendoen, D., Mitchell, B. R., Shriver, W. G., & Gibbs, J. P. (2009). Monitoring and evaluating the ecological integrity of forest ecosystems. *Frontiers in Ecology and the Environment*, *7*(6), 308-316. https://doi.org/10.1890/070176

Tilgenkamp, A. (2025, agosto 2). *Theil–Sen estimator [online]. MATLAB Central File Exchange.* https://www.mathworks.com/matlabcentral/fileexchange/34308-theil-sen-estimator

Torres, R. (2023, enero 24). Resistance In Chile's "State Of Exception". *Majority Post*. https://majoritypost.com/resistance-in-chiles-state-of-exception/

Torres, R., Azócar, G., Gallardo, R., & Mendoza, J. (2022). *Water Extractivism and Decolonial Struggles in Mapuche Territory, Chile*. *15*(1).

Torres, R., Azócar, G., Rojas, J., Montecinos, A., & Paredes, P. (2015). Vulnerability and resistance to neoliberal environmental changes: An assessment of

agriculture and forestry in the Biobio region of Chile (1974–2014). *Geoforum*, *60*, 107-122. https://doi.org/10.1016/j.geoforum.2014.12.013

Traganos, D., Poursanidis, D., Aggarwal, B., Chrysoulakis, N., & Reinartz, P. (2018). Estimating Satellite-Derived Bathymetry (SDB) with the Google Earth Engine and Sentinel-2. *Remote Sensing*, *10*(6), Article 6. https://doi.org/10.3390/rs10060859

Trenberth, K. E., & Hoar, T. J. (1996). The 1990–1995 El Niño-Southern Oscillation Event: Longest on Record. *Geophysical Research Letters*, *23*(1), 57-60. https://doi.org/10.1029/95GL03602

Troitskaya, Y., Rybushkina, G., Soustova, I., Balandina, G., Lebedev, S., & Kostianoy, A. (2012). Adaptive retracking of Jason-1 altimetry data for inland waters: The example of the Gorky Reservoir. *International Journal of Remote Sensing*, *33*(23), 7559-7578. https://doi.org/10.1080/01431161.2012.685972

UCM. (2024). *Earth Engine Data Catalog: TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces [online]. Merced, University of California Merced.* https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE#bands

University of North Carolina. (2025). *Mediciones en Lagos Red Ciudadana y Satelital*. LOCSS. https://www.locss.org/es

Upreti, G. (2023). Autopoiesis, Organizational Complexity, and Ecosystem Health. En G. Upreti (Ed.), *Ecosociocentrism: The Earth First Paradigm for Sustainable Living* (pp. 91-110). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-41754-2_5

Urrutia, R., Almanza, V., & Woelfl, S. (2022, septiembre 8). *Seminario proyecto: Levantamiento de información limnológica para la propuesta de NSCA de lagos nor-patagónicos* [[Discurso principal]. Seminario en línea.].

US EPA. (2011). *National wetland condition assessment: Field operations manual*.

US EPA. (2025). *Factsheets on Water Quality Parameters*. https://www.epa.gov/awma/factsheets-water-quality-parameters

US EPA, O. (2015, abril 16). *What is the National Lakes Assessment?* [Overviews and Factsheets]. https://www.epa.gov/national-aquatic-resource-surveys/what-national-lakes-assessment

USGS. (2025). *U.S. Geological Survey*. https://www.usgs.gov/

Valdés-Pineda, R., Cañón, J., & Valdés, J. B. (2018). Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals. *Journal of Hydrology*, *556*, 1153-1170. https://doi.org/10.1016/j.jhydrol.2017.01.031

Valdés-Pineda, R., Valdés, J. B., Diaz, H. F., & Pizarro-Tapia, R. (2016, junio 30). *Analysis of spatio-temporal changes in annual and seasonal precipitation variability in South America-Chile and related ocean-atmosphere circulation patterns.* | *EBSCOhost*. https://doi.org/10.1002/joc.4532

Vela, S. R. (2019). Método mayéutica y consultorías filosóficas en el siglo XXI. *Phainomenon*, *18*(2), 141-154. https://doi.org/10.33539/phai.v18i2.1745

Vera, R., & Rosner, C. (2020). *Recopilación y análisis de antecedentes para la revisión de la Norma Secundaria de Calidad Ambiental del lago Llanquihue*. ResearchGate. https://doi.org/10.13140/RG.2.2.29431.80801

Vergara Díaz, G., Vázquez, V. S., & Herrera Machuca, M. Á. (2018). Análisis del ambio temporal y espacial del uso del suelo en la región Centro-sur de Chile. *Ciência Florestal*, *28*, 1831-1844.

https://www.scielo.br/j/cflo/a/rtg7y6cGShDvQkMjWL7k47Q/?lang=es&format=html&stop=next
Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). *A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index*. https://doi.org/10.1175/2009JCLI2909.1
Vlasova, T., Petrov, A. N., & Volkov, S. (2021). Rethinking Sustainability Monitoring in the Arctic by Linking Resilience and Sustainable Development in Socially-Oriented Observations: A Perspective. *Sustainability*, *13*(1), Article 1. https://doi.org/10.3390/su13010177
Voulvoulis, N., Giakoumis, T., Hunt, C., Kioupi, V., Petrou, N., Souliotis, I., Vaghela, C., & binti Wan Rosely, WIH. (2022). Systems thinking as a paradigm shift for sustainability transformation. *Global Environmental Change*, *75*, 102544. https://www.sciencedirect.com/science/article/pii/S0959378022000826
Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., & Bierkens, M. F. P. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, *37*(20). https://doi.org/10.1029/2010GL044571
Wadoux, A. M. J.-C., & Minasny, B. (2024). Some limitations of the concordance correlation coefficient to characterise model accuracy. *Ecological Informatics*, *83*, 102820. https://doi.org/10.1016/j.ecoinf.2024.102820
Wakana, I., Kadono, Y., Urabe, J., Tamura, Y., Suzuki, Y., Yamada, H., Oyama, Y., Wada, K., Hasegawa, T., & Ohara, M. (2023). Varying stages of ecological succession in lakes subdivided by volcanic eruptions at Akan Caldera, Japan. *Hydrobiologia*, *850*(18), 3919-3933. https://doi.org/10.1007/s10750-023-05231-5
Wang, H., Qi, Y., Lian, X., Zhang, J., Yang, R., & Zhang, M. (2022). Effects of climate change and land use/cover change on the volume of the Qinghai Lake in China. *Journal of Arid Land*, *14*(3), 245-261. https://doi.org/10.1007/s40333-022-0062-4
Warner, S., Blanco Ramírez, S., de Vries, S., Marangu, N., Ateba Bessa, H., Toranzo, C., Imaralieva, M., Abrate, T., Kiminta, E., Castro, J., de Souza, M. L., Ghaffar Memon, A., Loiselle, S., & Juanah, M. S. E. (2024). Empowering citizen scientists to improve water quality: From monitoring to action. *Frontiers in Water*, *6*. https://doi.org/10.3389/frwa.2024.1367198
Westra, L., & Lemons, J. (2012). *Perspectives on Ecological Integrity*. Springer Science & Business Media.
Wetzel, R. G. (2001). *Limnology: Lake and River Ecosystems*. Gulf Professional Publishing.
Williams, J. (2021). *Climate change is racist: Race, privilege and the struggle for climate justice*. Icon Books. https://books.google.es/books?hl=es&lr=&id=RIQiEAAAQBAJ&oi=fnd&pg=PP8&dq=Williams,+J.+(2021).+Climate+change+is+racist:+Race,+privilege+and+the+struggle+for+climate+justice.+Icon+Books.&ots=NWw2BQCCgc&sig=7BuVe4PrQpNz7d1MptUcKTYDbj4
Willmott, C. J. (1981). On the Validation of Models. *Physical Geography*, *2*(2), 184-194. https://doi.org/10.1080/02723646.1981.10642213
Winkler, K., Fuchs, R., Rounsevell, M., & Herold, M. (2021). Global land use changes are four times greater than previously estimated. *Nature Communications*, *12*(1), 2501. https://www.nature.com/articles/s41467-021-22702-2

Winter, T. C. (1981). Uncertainties in Estimating the Water Balance of Lakes. *JAWRA Journal of the American Water Resources Association*, *17*(1), 82-115. https://doi.org/10.1111/j.1752-1688.1981.tb02593.x

WISDOM. (2025). *Objectives of the WISDOM Project*. https://wisdom.eoc.dlr.de/en/content/objectives-wisdom-project.html

WMO. (2025). *WMO Information System (WIS)*. https://old.wmo.int/extranet/pages/prog/www/WIS/

WMOa. (2025). *Observing Systems Capability Analysis and Review Tool (OSCAR)*. https://oscar.wmo.int/surface/#/

Wolodarsky-Franke, A., & Díaz, S. (2011). Cordillera de Nahuelbuta. *Reserva Mundial de Biodiversidad. Valdivia, Chile: WWF*.

Wongchuig, S., Carlo Espinoza, J., Condom, T., Junquas, C., Sierra, J. P., Fita, L., Sörensson, A., & Polcher, J. (2023). Changes in the surface and atmospheric water budget due to projected Amazon deforestation: Lessons from a fully coupled model simulation. *Journal of Hydrology*, *625*, 130082. https://doi.org/10.1016/j.jhydrol.2023.130082

Woods, S. (2025). How citizen science can help to solve the global freshwater crisis. *Nature*, *644*(8077), 582-582. https://doi.org/10.1038/d41586-025-02614-7

Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews Earth & Environment*, *1*(8), 388-403. https://doi.org/10.1038/s43017-020-0067-5

Woolway, R. I., Sharma, S., & Smol, J. P. (2022). Lakes in Hot Water: The Impacts of a Changing Climate on Aquatic Ecosystems. *BioScience*, *72*(11), 1050-1061. https://doi.org/10.1093/biosci/biac052

Woolway, R. I., Tong, Y., Feng, L., Zhao, G., Dinh, D. A., Shi, H., Zhang, Y., & Shi, K. (2024). Multivariate extremes in lakes. *Nature Communications*, *15*(1), 4559. https://doi.org/10.1038/s41467-024-49012-7

Wu, J., Li, W., Du, H., Wan, Y., Yang, S., & Xiao, Y. (2025). Nonlinear responses of coupled socioecological systems to land use and climate changes in the Yangtze river basin. *Scientific Reports*, *15*(1), 6940. https://doi.org/10.1038/s41598-025-92084-8

Wurtsbaugh, W. A., Paerl, H. W., & Dodds, W. K. (2019). Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *WIREs Water*, *6*(5), e1373. https://doi.org/10.1002/wat2.1373

Xu, J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Xu, W. (2022). Ecological Integrity Evaluation of Organically Evolved Cultural Landscape. *Mobile Information Systems*, *2022*(1), 9554359. https://doi.org/10.1155/2022/9554359

Xu (徐菊英), J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Yang, J., & Du, X. (2017). An enhanced water index in extracting water bodies from Landsat TM imagery. *Annals of GIS*, *23*(3), 141-148. https://doi.org/10.1080/19475683.2017.1340339

Yang, Xu, M., Li, R., Zhang, L., & Deng, Q. (2020). Estimating the ecological water levels of shallow lakes: A case study in Tangxun Lake, China. *Scientific Reports*, *10*(1), 5637. https://doi.org/10.1038/s41598-020-62454-5

Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J.-F., Wada, Y., & Berge-Nguyen, M. (2023). Satellites reveal widespread decline in global lake water storage. *Science*, *380*(6646), 743-749. https://doi.org/10.1126/science.abo2812

Zelený, J., Mercado-Bettín, D., & Müller, F. (2021). Towards the evaluation of regional ecosystem integrity using NDVI, brightness temperature and surface heterogeneity. *Science of The Total Environment*, *796*, 148994. https://www.sciencedirect.com/science/article/pii/S0048969721040663

Zhang, M., Lee, H., SHUM, C. K., Alsdorf, D., Schwartz, F., Tseng, K.-H., Yi, Y., Kuo, C.-Y., Tseng, H.-Z., Braun, A., Calmant, S., Filizola, N., & Seyler, F. (2010). Application of retracked satellite altimetry for inland hydrologic studies. *International Journal of Remote Sensing*, *31*(14), 3913-3929. https://doi.org/10.1080/01431161.2010.483495

Zhao, G., Li, Y., Zhou, L., & Gao, H. (2022). Evaporative water loss of 1.42 million global lakes. *Nature Communications*, *13*(1), 3686. https://doi.org/10.1038/s41467-022-31125-6

Zhao, Y., Feng, D., Yu, L., Wang, X., Chen, Y., Bai, Y., Hernández, H. J., Galleguillos, M., Estades, C., Biging, G. S., Radke, J. D., & Gong, P. (2016). Detailed dynamic land cover mapping of Chile: Accuracy improvement by integrating multi-temporal data. *Remote Sensing of Environment*, *183*, 170-185. https://www.sciencedirect.com/science/article/pii/S0034425716302188

Zhou, J., Leavitt, P. R., Rose, K. C., Wang, X., Zhang, Y., Shi, K., & Qin, B. (2023). Controls of thermal response of temperate lakes to atmospheric warming. *Nature Communications*, *14*(1), 6503. https://doi.org/10.1038/s41467-023-42262-x

Zhu, J., Peng, S., Shen, X., Lin, Z., Gong, L., Zhang, R., & Huang, B. (2024). Multiple scale impacts of land use intensity on water quality in the Chishui river source area. *Ecological Indicators*, *166*, 112396. https://doi.org/10.1016/j.ecolind.2024.112396

Zhu, L., Ju, J., Qiao, B., Liu, C., Wang, J., Yang, R., Ma, Q., Guo, L., & Pang, S. (2025). Physical and biogeochemical responses of Tibetan Plateau lakes to climate change. *Nature Reviews Earth & Environment*, *6*(4), 284-298. https://doi.org/10.1038/s43017-025-00650-5

Capítulo VI

Discusiones generales

En esta sección se presentan las discusiones generales de esta tesis doctoral. Para ello, en los primeros párrafos se sitúa este trabajo en un contexto global y local (Sección 1.). Luego se transitará la discusión en el mismo orden lógico que las tres hipótesis planteadas (Sección 2.). Para abordarlas, se recurrirá a los principales hallazgos desarrollados en los Capítulos II, III, IV y V, los cuales conjuntamente logran probar las tres hipótesis. Se sigue el orden lógico de las tres hipótesis, que a su vez siguen la lógica de causa-consecuencia-solución. Primero, se aborda de manera interdisciplinaria la pérdida de integridad natural/cultural del sistema costero – Cordillera de Nahuelbuta (H1). Luego, se analiza el efecto combinado del cambio climático y la pérdida local de integridad ecológica en la degradación del ciclo del agua y su calidad (H2). Además, entendiendo que para recuperar la integridad ecológica del sistema es necesaria la gestión ambiental desde un enfoque sistémico, esta tesis valida metodologías de monitoreo de calidad y cantidad de aguas, y propone su potencial uso en la gestión del agua (H3).

En la Sección 3. se abordarán aportes transversales para la gestión ambiental que surgen de esta tesis doctoral. El objetivo de esta sección es

integrar las cuatro variables clave estudiadas en un sistema de evaluación del territorio estudiado. Así, esta sección se convierte en un insumo para la gestión ambiental local, siendo útil por ejemplo en el proceso de levantamiento de norma secundaria de calidad ambiental o de iniciativas de restauración socio ecológica, procesos clave y de gran pertinencia local (ver Introducción).

En la Sección 4. , se delinean perspectivas y potenciales trabajos posteriores que en este proceso fueron abordados exploratoriamente en el marco de proyectos ambientales participativos. Se trata de experiencias prácticas y extensiones transdisciplinarias de esta tesis doctoral, que fueron posible únicamente disolviendo los límites de la mono-disciplina, e integrando conocimientos provenientes de las ciencias de la tierra por un lado y conocimientos de las ciencias socioambientales por otro. Estas experiencias son compartidas en detalle en los anexos: Appendix III.I y Appendix V.I, y aportaron con valiosos entendimientos para la maduración de esta discusión, permitiendo situar el trabajo en una realidad local con proyección en la gestión ambiental y proponer la hipótesis emergente H4 de que la ciencia ciudadana puede ser un pilar de la gestión ambiental.

1. Contexto global y local

Hay cierto consenso a nivel mundial de que hay una crisis ambiental sin precedentes y de que ella tiene que ver con los estilos de vida que ha adoptado la humanidad en general. En América Latina, esta situación se interpreta como resultado de una historia de colonización y desarrollo extractivista, donde los modelos de desarrollo han degradado radicalmente los ecosistemas (Gudynas, 2015; Martínez Retureta, 2021). Además de lo anterior, experimentamos las consecuencias de un cambio climático desigual: las potencias mundiales, siendo las que más emisiones de dióxido de carbono han aportado históricamente, tienen una baja vulnerabilidad frente al cambio climático. Las consecuencias del cambio climático las pagan los países vulnerables, ubicados principalmente en América Latina, sur de Asia y África (Choongik, 2025; Cuomo, 2011; Odeku, 2022; Williams, 2021).

Este cambio, inducido por las emisiones acumuladas de gases de efecto invernadero de todos los países ha elevado la temperatura media global, que ha alcanzado el nivel récord de 1,75ºC con respecto a niveles pre-industriales (Copernicus Climate Change Service, 2025). Esto ha generado efectos locales como veranos más calurosos, inviernos más fríos, lluvias extremas en momentos inusuales del año o sequías prolongadas. Los eventos climáticos extremos se han vuelto más frecuentes desde el siglo XX (Yi et al., 2015), dando lugar a desastres como olas de calor, sequías, inundaciones

(Dai et al., 2018a; J. Huang et al., 2020), incendios, reducción de biodiversidad y problemas de acceso al agua y alimentos. En Chile central (30°–38°S), desde 2010 se ha observado además la Megasequía, con déficit de precipitaciones de entre el 25 % y 45 % (Garreaud et al., 2020), lo que agrava aún más el escenario local. Necesitamos directrices claras sobre cómo hacer frente a la crisis ambiental ahora, con las herramientas que tenemos a nuestra disposición.

Bajo el concepto de integridad ecológica, esta tesis doctoral buscó caracterizar el sistema costero – Cordillera de Nahuelbuta con foco en los Lagos Nahuelbutanos. La caracterización es parcial y se enfoca en el paisaje mediante la cobertura/uso del suelo y el metabolismo socio-ecológico; y en el agua mediante parámetros de calidad (temperatura del agua), y cantidad de agua (nivel del agua del lago). Estos indicadores en su conjunto constituyen un estudio parcial de integridad ecológica, que sirve de base para ampliar la caracterización de estado del sistema.

La tesis se sitúa en un valioso sistema en Chile centro-sur: el sistema costero - Cordillera de Nahuelbuta, sus Lagos Nahuelbutanos y la relación con su gente. Este sistema alberga una naturaleza diversa en ecosistemas (ríos, lagos, humedales, estuarios, bosque nativo, dunas, etc.) con gran cantidad de especies endémicas (Wolodarsky-Franke & Díaz, 2011), además de una riqueza cultural enorme debido a la confluencia de las comunidades mapuche con prácticas de miles de años de antigüedad, comunidades campesinas y

rurales con prácticas tradicionales centenarias y las zonas urbanas principalmente cerca del núcleo urbano del Gran Concepción (Araya, 2019).

2. Testeo de hipótesis

H1 plantea que el sistema costero – Cordillera de Nahuelbuta ha sido degradado o desintegrado mediante la ruptura del metabolismo socio-ecológico a escala local y debido al cambio climático a escala global. Para decir que ha sido degradado, en el Capítulo II se caracteriza la degradación como pérdida de integridad de tipo natural/cultural, lo que prueba la degradación del sistema costero – Cordillera de Nahuelbuta debido a la fractura del metabolismo socio-ecológico. Para este análisis, el estudio se sitúa a escala de paisaje. Lo que se hace es delimitar ecosistemas originales o sistemas naturales (ej.: bosque nativo, praderas y matorrales, humedales) y sistemas antrópicos (ej.: monocultivo forestal, zonas urbanas, zonas agrícolas) en un momento original (1550) y uno actual (2015-2024). En paralelo, con cada sistema natural y antrópico se caracteriza el metabolismo socio ecológico, es decir, cómo ha sido y cómo es la relación de las comunidades humanas con esos sistemas. De esta manera podemos vislumbrar lo que había, lo que hay y lo que se ha perdido. En este capítulo, se interpreta la degradación de la Naturaleza a escala local como la fractura antropogénica producida por el cambio en el metabolismo socio ecológico (Foster, 2022). Bajo el supuesto de que, así como el sistema se degradó por

acción humana, se puede recuperar por acción humana, la motivación de este capítulo es poder vislumbrar procesos de restauración socio-ecológica, espacializados, y vinculados a prácticas humanas. Por eso, esta parte de la tesis doctoral (Capítulo II) es un gran insumo para iniciativas de conservación y restauración socio ecológica a escala de paisaje, y en la Sección 2. de esta discusión se presenta cómo esto se operacionaliza en un sistema de evaluación de estado del territorio.

Los resultados del Capítulo II revelan una drástica reducción del bosque nativo de las ¾ a ¼ del territorio, la pérdida de las praderas y matorrales que se mezclaban con humedales para sostener los asentamientos humanos que se redujo del 23% al 11%. En paralelo, la expansión de la plantación forestal exótica de cero a la mitad del territorio, junto con la agricultura y la agricultura intensiva que ahora ocupa la cuarta parte. La masividad del cambio a escala de paisaje ha sido producida por un cambio en el metabolismo socio-ecológico.

Desde la perspectiva de la integridad natural/cultural, el estado original precolonial puede entenderse como un paisaje en equilibrio, donde los ecosistemas naturales (bosque, praderas, matorrales y humedales) se entrelazaban con los sistemas humanos, generando un territorio que mantenía sus funciones ecológicas y sustentaba comunidades humanas no menores. Este equilibrio era posible gracias a una naturaleza abundante que proveía alimentos, medicina y refugio, contextualizado en un clima lluvioso. La

relación sociedad-naturaleza estaba marcada por la reciprocidad de una sociedad que se articulaba en torno a los ciclos del sistema natural, con un sistema de conocimiento enmarcado en una cosmovisión que otorga un valor intrínseco a la naturaleza y que comparte con ella una espiritualidad. Todo lo anterior, reproducía un sistema socio-ecológico íntegro y resiliente.

En el estado actual, en contraste, se observa la pérdida de esa integridad natural/cultural: los ecosistemas se encuentran fragmentados y profundamente transformados, donde sus flujos de agua son erráticos, con eventos de lluvia extrema e inundaciones contrastados con eventos de poca precipitación y sequía. Los cuerpos de agua están contaminados, los sistemas lacustres eutrofizados, lo que no permite el acceso al agua sin una intervención humana intermedia, a diferencia de antaño. Esta situación está enmarcada en una cosmovisión donde la naturaleza es concebida principalmente como una fuente de bienes y servicios que sustenta la economía. El cambio del primer estado al segundo, se interpreta teóricamente como una fractura antropogénica, es decir, la ruptura del metabolismo socio-ecológico que produjo la degradación de la naturaleza, dando lugar a un sistema intervenido intensivamente, que depende de asistencia humana para funcionar, desintegrado, con desastres naturales como floraciones algales en sistemas lacustres, megaincendios forestales, sequías e inundaciones. Este sistema se reproduce a si mismo a través de distintas estructuras políticas,

sociales, económicas, ambientales y culturales, lo que le otorga una resiliencia no deseada.

La pérdida de integridad natural/cultural local se enmarca en tendencias globales ampliamente respaldadas bajo los marcos teóricos de antropoceno (Lewis & Maslin, 2015), la fractura antropogénica (Foster, 2022) o los límites planetarios (Rockström et al., 2024), como pudo apreciarse en la Sección 1. de esta discusión.

La integridad natural/cultural baja en el sistema de estudio da cuenta de la magnitud de la degradación. Con respecto a esto, en el Capítulo II se analiza la degradación de la naturaleza considerando la extensión histórica del conflicto. Se evidencia que hay tres hitos históricos que juegan un rol principal en la degradación del sistema: la Colonización española, la Ocupación de la Araucanía y la Dictadura militar. Un punto importante es que el sistema no habría sido intervenido sustancialmente durante la Colonización española, debido a la resistencia del pueblo Mapuche que marcó una frontera en el río Biobío, impidiendo la colonización hacia el sur. No obstante, en esta primera colonización, si se sentaron las bases de la configuración territorial que tenemos hoy: Concepción como núcleo urbano (y punto de penetración hacia el sur en la Ocupación de la Araucanía), y el sur del territorio como zona de resistencia Mapuche. No fue sino hasta la Ocupación de la Araucanía que se despoja a los habitantes nativos, se ocupa sus tierras con colonos y se cambia completamente el metabolismo socio ecológico. Luego, en la

Dictadura militar, mediante políticas públicas neoliberales, se altera nuevamente el metabolismo socio ecológico a gran escala, con la inserción masiva del monocultivo forestal. En esta línea, se da cuenta de la fuerza de la dimensión política en la degradación del sistema, que tiene una extensión histórica que se remonta 500 años atrás. En este contexto, el rol que juegan las autoridades, los cuerpos legales y las políticas públicas cobran un rol que es capaz de moldear la degradación o restauración. El rol que tomen las instituciones y los actores políticos es trascendental en este problema, así ha sido hasta ahora.

En el Capítulo IV y el Capítulo V, se evalúa el alcance de la fractura antropogénica en el ciclo hidrológico y la calidad del agua (tributando al testeo de la H2), mediante herramientas satelitales y de modelación, junto con bases de datos públicas globales y nacionales. A lo largo de los capítulos, se operacionaliza el concepto de integridad hidrológica, a través del monitoreo de variables clave asociadas a la calidad y cantidad del agua: la temperatura y el nivel del agua del lago, respectivamente, en el Lago Lanalhue, en el largo plazo, lo que permite establecer tendencias asociadas al cambio climático. Por lo anterior, el Capítulo IV y el Capítulo V tributan también a la H1 en lo concerniente al cambio climático. El Lago Lanalhue es escogido como caso específico para desarrollar el Capítulo IV y el Capítulo V debido a que es el único que dispone de datos de nivel y temperatura del agua de largo plazo, así como estudios previos, lo que permite validar las metodologías de

percepción remota y modelación para extrapolarlas a otros cuerpos de agua en una etapa posterior a esta tesis doctoral. Además, este lago es parte de la contingencia ambiental local, porque se está actualmente construyendo su NSCA, por lo que se convertiría en el tercer lago de Chile con esta norma. Por lo anterior, este estudio académico también pretende aportar a ese propósito, enriqueciendo el estado del arte del Lago Lanalhue y proveyendo con marcos teóricos y herramientas para el seguimiento de su estado y su gestión.

Como adelanté en la introducción, reconozco que todos los Lagos Nahuelbutanos poseen una importancia equivalente a la del caso estudiado. No obstante, la extensión limitada de una tesis doctoral de tres años y la rigurosidad metodológica necesaria, impidieron profundizar en todos ellos.

Metodológicamente, en el Capítulo IV se modela la estructura térmica vertical del Lago Lanalhue mediante el modelo hidrodinámico avanzado 3D: COHERENS, validado con datos in-situ e imágenes Landsat. Esta modelación permite describir de manera detallada los procesos de estratificación, mezcla y distribución espacial de la temperatura, elementos clave para comprender la dinámica trófica y el transporte de contaminantes. En el capítulo V, se estudia la cantidad de agua en los lagos mediante series temporales de nivel lacustre desde 1950, integrando altimetría (Sentinel-3A) y modelación hidrológica conceptual forzada por datos meteorológicos reales in-situ y bases de datos hidroclimáticas (ERA5-Land), lo que permite sacar conclusiones acerca de la crisis hídrica que se manifiesta como escasez de agua en la zona.

El análisis hidro-físico del Capítulo IV y el Capítulo V revela un patrón de calentamiento progresivo en la unidad de estudio Lago Lanalhue, de 0.12°C por década entre 2001 y 2024, lo cual es el reflejo local de las tendencias globales de cambio climático, sumado a los mal usos del suelo y a la pérdida de coberturas vegetales nativas que modulan los flujos hídricos y térmicos (Martínez Retureta, 2021). Al comparar las estaciones, el calentamiento más grande ocurre en verano, con una tendencia de 0.18 °C por década. Esta estación del año es donde ocurre la mayor cantidad de los destructivos mega incendios en las regiones con mayor cobertura de plantación forestal del país, especialmente en las regiones de Maule, Biobío y Araucanía (Ortiz et al., 2024). En sistemas lacustres, las cada vez más frecuentes floraciones algales y el envejecimiento acelerado (eutrofización), dan cuenta también de un cambio dramático de estado. En paralelo, se evidencia una disminución sostenida de la cantidad de agua, reflejada en una reducción del nivel del agua de ~5 cm por década desde 1950 en el Lago Lanalhue, asociada con la disminución de precipitaciones y el aumento de la evaporación superficial.

Esta tesis reconoce limitaciones metodológicas que orientan mejoras futuras. Primero, la resolución temporal de Landsat (ocho días al combinar L8 y L9) se ve reducida por el descarte de escenas con nubosidad, llegando en algunos casos a una o ninguna imagen disponible por mes. Esto permite estudiar patrones estacionales, pero dificulta la interpretación interanual o de

largo plazo, y por lo tanto, la construcción de estados de referencia históricos confiables. Este déficit puede mitigarse mediante modelos numéricos forzados con datos meteorológicos horarios, razón por la cual, en el Capítulo IV se extendió el estudio de la TSAL en el tiempo con el modelo 3D COHERENS. Se han hecho incluso estudios asimilando datos satelitales en modelos 3D, lo que abre vías robustas para superar dicha restricción.

La segunda limitación es la escasez de datos in situ, un problema extendido en la mayor parte de Sudamérica. Desde la academia existe la necesidad de validar rigurosamente las metodologías en un lago con mayor observación (Lanalhue), que a su vez es el único que prontamente contará con norma. No obstante, los tiempos que toma validar los modelos no van acorde con la urgencia en la gestión. La validación de los modelos facilita extrapolar las metodologías al resto de los lagos, aunque persiste una dependencia mínima de mediciones locales para evitar errores gruesos en las simulaciones. Esto es abordable fortaleciendo el muestreo estatal (más frecuente, en más cuerpos de agua y coordinado con los sobrevuelos de Landsat y Sentinel) y promoviendo la ciencia ciudadana, que no solo amplía la base de datos sino que incorpora a las comunidades en la gestión de sus aguas. De este modo, las soluciones no son solo técnicas: requieren también capacidades institucionales.

La articulación de los Capítulos II, IV y V, permite constatar que las alteraciones en el metabolismo socio-ecológico descritas en el Capítulo II se

gestaron a partir de la colonización española en 1550, se profundizaron con la Ocupación de la Araucanía desde 1881 y se intensificaron con la Dictadura militar desde 1973. Sumado al cambio climático desigual, dichos procesos desencadenaron un cambio en el ciclo hidrológico a partir de 1950 que se traduce en escasez de agua. Así mismo, degradaron progresivamente la calidad del agua, que se traduce en el aumento progresivo de la temperatura del agua. Las variaciones en dos variables físicas del sistema lacustre (temperatura y nivel del agua), constituyen manifestaciones concretas de un cambio estructural que se expresa en la integridad hidrológica, lo que corrobora la H2, pero que también se expresa en todas las dimensiones del sistema socio-ecológico. La pérdida de integridad hidrológica observada en el Lago Lanalhue coincide con estudios recientes que documentan el descenso del nivel de los lagos y el calentamiento progresivo de sus aguas como respuesta combinada a forzantes climáticos y cambios de uso del suelo (Piccolroaz et al., 2024b; Sullivan et al., 2025).

Un ejemplo muy relevante en relación con el ciclo hidro-social, que en términos de integridad podría llamarse integridad hidrológica/cultural, es la degradación del estado del agua (calidad y cantidad) y el cambio radical en la relación de las personas con ella. En el estado de referencia del ecosistema, la calidad del agua permitía abastecerse directamente desde los cuerpos de agua: “ibas y sacabas el agua directamente del río o del cuerpo de agua” (E10, 2022). Los cuerpos de agua: napas, vertientes, lagos, ríos, eran fuente directa

de agua para consumo humano. Sin embargo, hoy en día no es posible: debido a la contaminación, el acceso al agua directamente de los ecosistemas es peligroso. Debido a la escasez, en muchas localidades no hay siquiera agua disponible. Para asegurar agua de calidad apta para consumo humano, existen ahora los sistemas de tratamiento de aguas en zonas urbanas, y los sistemas de agua potable rural (APR) en zonas rurales, que reemplazan la relación directa con la naturaleza por una gestión humana intermedia. Para asegurar la disponibilidad de agua ante emergencias, ante sequías, o falta de agua en general, existen los camiones aljibe, cuya función es distribuir agua en camiones. Esta transformación, además de cambiar toda la relación metabólica de las comunidades humanas con los ecosistemas, ha contribuido a la privatización del acceso al agua, y ha expuesto a las personas a la inseguridad hídrica debido a negligencia de distintos niveles. Desde problemas en la mantención: a veces “en el verano no tenían agua, pero era porque no había mantención” (E10, 2022). A problemas estructurales donde la degradación implica la no disponibilidad absoluta de agua, lo que se soluciona con los camiones aljibe. En algunas localidades, por ejemplo, en la comuna de Tirúa, “la gente ya lleva como 10 años con camiones aljibe” (E10, 2022). Una solución de emergencia como lo son los camiones aljibe, se ha generalizado y normalizado como sistema de abastecimiento del agua, lo que da cuenta de un problema estructural de precariedad hídrica, donde la funcionalidad mínima de los ecosistemas no está asegurada.

Este fenómeno de transformación, de cambio de integridad ecológica, puede interpretarse desde el concepto de “tipping points”. En el marco de la teoría de resiliencia ecológica, los tipping points se entienden como umbrales críticos en los cuales un sistema cambia abruptamente de un estado estable a otro, generalmente difícil de revertir. Este concepto permite interpretar los procesos de transformación ambiental como posibles transiciones entre regímenes de estabilidad ecológica y social (Scheffer et al., 2001). El cambio climático constituye un proceso de este tipo, al poder ser entendido como un salto del sistema climático entre estados estables (Dai et al., 2018b), lo que se evidencia en múltiples variables como como temperatura, presión atmosférica, régimen de vientos y precipitaciones. Un determinado clima también influenciará las prácticas de subsistencia, la vegetación y todas las formas de vida en un lugar. Los cambios observados en el sistema costero – Cordillera de Nahuelbuta y en sus sistemas hídricos, en particular lacustres, probablemente están representando el traspaso de ciertos umbrales críticos que han marcado el tránsito hacia un nuevo estado del sistema, resiliente y estable, en todas sus dimensiones. En este nuevo estado, el sistema reproduce condiciones desfavorables para la vida. Incluida la humana, como los mega incendios, el aumento del grado trófico por eutrofización, la contaminación y escasez de agua, la reducción de la biodiversidad, etc. En la Sección 4. de esta discusión, se hablará de algunas recomendaciones para gestionar los sistemas acuáticos de tal manera de mantenerse dentro de ciertos umbrales que aseguran la integridad del sistema.

En H3 se busca probar que las herramientas de teledetección y modelación numérica pueden integrarse en el monitoreo ambiental para una gestión efectiva de los Lagos Nahuelbutanos. Para esto, en los Capítulos III, IV y V, se validan estadísticamente las metodologías desarrolladas. Los estadísticos utilizados son R-cuadrado (R^2), y errores cuadráticos medios normalizados (*NRMSE*). La motivación de estos tres capítulos es, además de contribuir al estado del arte de los Lagos Nahuelbutanos, aportar con metodologías validadas al monitoreo ambiental, sin incurrir en un costo adicional, sino que, usando herramientas disponibles, datos de libre acceso globales, y datos públicos nacionales. Se busca poner el conocimiento técnico de tecnologías avanzadas al servicio de una gestión ambiental accesible para todos los territorios.

En el Capítulo III, se implementa una innovadora metodología en Google Earth Engine para obtener series temporales de temperatura superficial del agua (TSAL) en lagos medianos y pequeños. La metodología es validada para la Laguna Grande de San Pedro y el Lago Lanalhue y extrapolada a 25 Lagos Nahuelbutanos, con el objetivo de caracterizar el ciclo anual de los lagos Nahuelbutanos como distrito de lagos que comparten una base geológica y climática común, analizando la diferenciación térmica inter-lacustre. Esta variable es un indicador clave de la calidad del agua y se relaciona directamente con procesos de eutrofización y floraciones algales nocivas, eventos que han aumentado en frecuencia e intensidad en la zona

de estudio (Almanza et al., 2016; Meerhoff et al., 2022; O. Parra et al., 2005b). Los métodos de teledetección para obtener la TSAL a partir de archivos Landsat fueron validados con datos in-situ en dos lagos (Laguna Grande de San Pedro y Lago Lanalhue), y se obtuvieron las siguientes métricas: $R^2 \geq 0.87$ y *NRMSE* más bajo que 0.12.

En el Capítulo IV, la validación de la modelación hidrodinámica avanzada usando el modelo 3D COHERENS para obtener TSAL en el Lago Lanalhue muestra las siguientes métricas con respecto a perfiles de temperatura in-situ: R^2: 0.69–0.97 y *NRMSE*: 0.12–0.23, indicando un excelente desempeño del modelo. Finalmente, en el Capítulo V, en cuanto al uso de altimetría para obtener nivel del agua de un lago, la validación muestra valores de *NRMSE* = 0.0863 y $R^2 = 0.8573$. Los resultados muestran muy buen desempeño de los datos satelitales térmicos, altimétricos y del modelo COHERENS para reproducir la variabilidad estacional e interanual de los lagos estudiados. Lo anterior demuestra la confiabilidad y escalabilidad de estas herramientas para la gestión ambiental, lo que permite probar la H3 de esta tesis doctoral.

La validación de las herramientas de teledetección y modelación desarrolladas en esta tesis se alinea con trabajos recientes que demuestran la efectividad de la observación remota para el monitoreo de calidad del agua y la gestión hídrica a distintas escalas (Batina & Krtalić, 2024; Ngamile et al.,

2025). Estas investigaciones destacan la integración de sensores satelitales y técnicas de modelación como pilares de la gestión ambiental moderna.

3. Aportes transversales para la gestión ambiental

La superación de la NSCA activa la elaboración de planes de descontaminación que se enfocan principalmente en reducir las emisiones de nutrientes al lago por parte de los focos de contaminación (industrias, residuos domésticos) (MMA, 2020). Pero las causas de la superación de la norma trascienden al input de nutrientes. Como se ha visto hasta ahora, responden además a las condiciones climáticas de base o a la presencia o ausencia de cobertura nativa, entre otros. La complejidad de los sistemas socio-ecológicos presenta desafíos no menores para la gestión ambiental, en el marco de la institucionalidad vigente (Wu et al., 2025). Para abordar este desafío, es necesario situarse desde enfoques más holísticos basados en sistemas socio-ecológicos, como la integridad ecológica.

Esta investigación representa un aporte teórico para la conceptualización de la degradación ambiental con enfoque de sistema socio-ecológico, mediante la aplicación del marco teórico de integridad ecológica (natural/cultural e hidrológica), a un sistema socio-ecológico de Chile centro-sur. Aunque el concepto de integridad ha sido trabajado en contextos internacionales, aquí se le da pertinencia para situarse en el territorio costero–Cordillera de Nahuelbuta con foco en sus sistemas lacustres, mostrando cómo

puede operacionalizarse costo-efectivamente, utilizando en su mayoría bases de datos públicas y de libre acceso, mediante indicadores de cobertura de suelo, metabolismo socio-ecológico y calidad y cantidad de agua. Además, el estudio integra en este marco transversal de la integridad ecológica, otros marcos teóricos relevantes que vienen de las ciencias sociales como la fractura antropogénica; o marcos teóricos que provienen de las ciencias físicas como el monitoreo de ecosistemas en base a sensores remotos. Así, se recoge desde la academia información disciplinaria muy relevante por si sola, pero además se integra para operacionalizar un marco metodológico interdisciplinario para situarnos y actuar frente a la degradación de la naturaleza.

En este trabajo, la integridad ecológica se operacionaliza mediante cuatro variables que capturan principalmente las dimensiones hidrológicas y sociales; por lo tanto, las inferencias que se derivan del análisis se restringen a esas dimensiones. En consecuencia, no se abordan otros componentes, como la biodiversidad o la cadena trófica, que suelen incorporarse en evaluaciones de estado de ecosistemas. Cabe señalar que la mayoría de los estudios sobre integridad ecológica han desarrollado variables principalmente en la dimensión biofísica, existiendo menos estudios que incorporen dimensiones sociales, económicas o culturales, lo que, en la práctica, también delimita el alcance operacional de este marco teórico.

En esta sección se presentan los aportes transversales que se desprenden de este trabajo para la gestión ambiental. El objetivo es proponer un modelo de evaluación de integridad ecológica en base a las variables o indicadores utilizados (ver Tabla VI.1). Para esto, se utilizará una escala semáforo que suele utilizarse para la evaluación de integridad ecológica (Tierney et al., 2009; Zelený et al., 2021). Además, entendiendo que algunos de los umbrales presentados ya han sido superados, se proponen iniciativas de restauración socio-ecológica levantadas en base a esta investigación y a revisión bibliográfica.

Tabla VI.1: Modelo de evaluación de integridad ecológica en base a escala semáforo, construida a partir de la investigación realizada y revisión bibliográfica.

Tipo de integridad	Variable	Integridad			Estado
		Alta	Media	Baja	
Natural/ cultural a escala de paisaje	Cobertura/ uso del suelo	Uso antrópico intensivo < 10%	Uso antrópico intensivo entre 10 y 30%	Uso antrópico intensivo > 30%	Integridad baja en el sistema costero - Cordillera de Nahuelbuta
		Bosque nativo > 60%	Bosque nativo entre 40 y 60%	Bosque nativo < 40%	
	Metabolismo socio-ecológico	Conocimiento tradicional activo y presente masivamente en prácticas de manejo sostenibles y en sincronía con el ciclo estacional	Conocimiento tradicional y prácticas sostenibles coexisten con prácticas extractivas intensivas en una proporción similar	Pérdida o marginación del conocimiento tradicional y dominancia de prácticas extractivas intensivas	
		Acceso y control/propiedad de los ecosistemas y sus recursos (agua, alimentos, materiales, medicina)	No hay control/propiedad del privado, pero hay acceso a los ecosistemas y sus recursos	No hay control ni acceso a los ecosistemas ni sus recursos	
Hidrológica en sistemas lacustres	Temperatura del agua	Tendencia pequeña ≲ 0.1 °C por década	Tendencia entre ~0.1-0.3 °C por década	Tendencia > 0.3 °C por década	Integridad media en el Lago Lanalhue
	Nivel del agua	Cambios históricos menores a -0.35 m y nivel actual > -	Cambios históricos mayores que -	Nivel < -0.35 m	Integridad media en el Lago Lanalhue

		0.35 m (NAE porción somera)	0.35 m, pero nivel actual > -0.35 m		

3.1. Integridad natural/cultural

3.1.1. Cobertura/uso del suelo

Definir el umbral de cobertura/uso del suelo a partir del cual un sistema socio-ecológico pierde integridad es complejo, porque varía con el tamaño de la cuenca hidrográfica (Lee et al., 2023) y el tipo de cobertura (urbana, agrícola, forestal) (Locke, 2024). En sistemas forestales, un 25–60% de cobertura de bosque nativo ayuda a mantener la calidad del agua y la integridad biológica (Lee et al., 2023), y un ~60% de cobertura nativa permite la existencia de hábitat continuo (Tierney et al., 2009).

Para la agricultura, los umbrales son amplios (5–70%), probablemente porque dependen del tamaño de la cuenca y de cuán intensiva sea la agricultura. Si es menos intensiva (ej.: paisajes más bioculturales/multifuncionales con manejo ribereño), se pueden tolerar mayores proporciones de agricultura (Lee et al., 2023).

Para la urbanización, la calidad del agua disminuye por sobre 35–40% de cobertura urbana en cuencas grandes y por sobre 5–10% en cuencas pequeñas (Lee et al., 2023). En general, 10–15% ya provoca degradación

acuática (Locke, 2024), y alrededor de 31%, el sistema puede dejar de responder a la gestión, indicando un tipping point (Zhu et al., 2024).

A escala de paisaje completo, la integridad en sistemas forestales disminuye claramente bajo ~40% de cobertura nativa (Tierney et al., 2009).

Con base en la revisión de literatura anterior, en este trabajo se plantea lo siguiente. Un territorio se encuentra en un estado de alta integridad cuando el uso antrópico intensivo (forestal, urbano y agricultura intensiva) es < 10% de la cobertura, asociado a la pérdida de degradación en pequeñas cuencas, y una cobertura de bosque nativo de un 60%, asociado al umbral que propone (Tierney et al., 2009). En ese caso, las superficies intervenidas representan un máximo de un 40% de la superficie. Un estado de integridad media se asocia con un uso antrópico intensivo de hasta un 30%, asociado al umbral propuesto por Zhu et al. (2024), junto con una cobertura de bosque nativo no inferior a un 40%. Un estado de baja integridad ocurre cuando el uso antrópico intensivo es > 30% y la cobertura de bosque nativo es menor que un 40% (Tabla VI.1: Modelo de evaluación de integridad ecológica en base a escala semáforo, construida a partir de la investigación realizada y revisión bibliográfica.).

Aplicando el modelo generado para el área de estudio, se obtiene lo siguiente. El 51% de la cobertura/uso del suelo actual corresponde a monocultivo forestal, una actividad extractiva intensiva y dominante (ver

Capítulo II). Con este número, el sistema ya clasifica en un estado de baja integridad con respecto a esta variable. Ahora bien, es interesante hacer el análisis por cuenca. En algunos casos, la situación empeora. De siete cuencas de Lagos Nahuelbutanos analizadas (Lagunas Grande y Chica de San Pedro, Junquillar-Posada, Quiñenco, Lagos Lanalhue y Lleulleu, ver Appendix VII.I), se encontró lo siguiente: mientras la cobertura forestal en algunas cuencas disminuye (ej.: 35% en Antihuala), en otras aumenta llegando al 70% (Lagunas Posada-Junquillar y Quiñenco). En el caso de la cobertura urbana, esta oscila entre 0 y 18%, siendo las mayores la Laguna Chica de San Pedro (13%), Laguna Grande de San Pedro (15%) y Laguna Antihuala (18%). Lamentablemente, si se suman los usos intensivos presentes en las cuencas (ver Appendix VII.I), en todas las cuencas se supera el 40%, lo que supone alteraciones importantes en la estructura, función y composición, y por lo tanto denota una integridad baja en todos los casos analizados.

Lo anterior, debiera disparar mecanismos de control, por ejemplo, mecanismos incorporados en un Programa para la Recuperación Ambiental y Social (PRAS), tomando como unidad las microcuencas, que vaya en la línea de detener los forzantes de la degradación, vía regulación de cobertura/uso del suelo. Así, se debiera trabajar en dos frentes. El primero es reducir el uso intensivo en extensión espacial, tomando como unidad de análisis la cuenca, preocupándose de distribuir bien los usos intensivos y no sobrecargar una cuenca en desmedro de otras. El segundo es volver los usos intensivos menos

intensivos, otorgándole a los sistemas antrópicos mayor diversidad a escala del paisaje. Un marco teórico importante para guiarse en estos casos son los paisajes multifuncionales, en este caso, uso del suelo multifuncional. Por ejemplo, el paisaje forestal multifuncional, que busca responder simultáneamente tanto a las demandas económicas (producción de madera) como ecológicas y sociales sobre los bosques (conservación de la biodiversidad, recreación, servicios ecosistémicos, valores culturales y espirituales) (Schmithuesen, 2007). Aplicado a las zonas urbanas, el concepto de multifuncionalidad involucra planificación urbana, servicios ecosistémicos, sustentabilidad y adaptación climática. Para lograrlos se requiere abordar el elementos como la distribución espacial, accesibilidad y participación social (Korkou et al., 2023). En el contexto de la agricultura, cuando ella es multifuncional, además de producir, gestiona recursos, conserva paisajes/biodiversidad y sostiene economías rurales (Renting et al., 2009). Incluso hay extensiones a interfaz urbano-agrícola (Lovell, 2010) o agrícola forestal (Cheng et al., 2024; Guo et al., 2023).

Pero regular el uso intensivo del suelo no es tan fácil. En el área de estudio, estos usos intensivos son llevados a cabo por empresas que tienen poder en la toma de decisiones a nivel nacional (Manuschevich, 2016). Un caso polémico es la industria forestal, promovida por el D.S. 701 que promueve su desarrollo desde 1974. En presente gobierno, Gabriel Boric intentó poner sobre la mesa la discusión sobre la necesidad de regular el

desarrollo forestal, en vista de los megaincendios del verano de 2023 (EMOL, 2023). No obstante, hubo una respuesta discursiva que se opuso fuertemente a esta idea por parte de gremios productivos como la SOFOFA, y la Confederación de la Producción y del Comercio (CPC) (Interferencia, 2023). SOFOFA y CPC catalogaron abrir este debate como “improcedente y fuera de contexto” (SOFOFA), o “cuestionar hoy día una industria que da miles de empleos es impropio” (CPC) (Bio Bio, 2023). Con lo anterior, se reafirma el impacto que aún tiene la dimensión política en la reproducción de estados indeseables, mediante el poder de propiedad sobre las tierras (Manuschevich, 2016).

3.1.2. Metabolismo socio-ecológico

Se observa un metabolismo socio-ecológico de alta integridad cuando el conocimiento tradicional está activo y ampliamente presente en las prácticas de gestión sostenible, en consonancia con los marcos de restauración socio ecológica y actividades humanas de bajo input (Altieri y Rojas, 1999; Tedesco et al., 2023). Además, las comunidades conservan el acceso y el control/propiedad de los ecosistemas y sus recursos (agua, alimentos, materiales, medicinas), lo que sustenta los vínculos metabólicos entre la sociedad y la naturaleza. Esto es evidenciado en ejemplos como los títulos de tierras indígenas que reduce el desmonte y las perturbaciones (Blackman et al., 2017), la formalización de la propiedad mejora los resultados

forestales (Benzeev et al., 2023) y, a nivel mundial, el reconocimiento de los derechos territoriales indígenas que es esencial para alcanzar los objetivos de conservación (Garnett et al., 2018).

En un estado de baja integridad, el metabolismo socio-ecológico se caracteriza por la pérdida o marginación del conocimiento tradicional y por el predominio de prácticas extractivas intensivas. Simultáneamente, el acceso y el control sobre los ecosistemas y sus recursos se reducen mediante la apropiación de tierras y recursos, lo que fractura los vínculos históricos entre la sociedad y el territorio y profundiza la degradación ecológica (Bebbington et al., 2018; Ostrom et al., 1999; Reyes-García et al., 2013).

Un nivel de integridad media se sitúa en un punto medio: el conocimiento tradicional y las prácticas sostenibles aún están presentes, pero coexisten con prácticas extractivas intensivas en una proporción similar. En estos casos, ya no existe control total ni propiedad sobre los ecosistemas, pero aún hay acceso a ellos y a sus recursos.

Analizando el territorio de estudio, las personas perciben la actividad forestal como hegemónica (ver Capítulo II), que a través de la propiedad no permite el acceso a los ecosistemas y sus recursos. La industrialización y su infraestructura asociada (por ejemplo, el Parque Industrial en Coronel), junto con la urbanización privatizan y fragmentan el territorio, impidiendo el control y el acceso (ver Capítulo II). Por otro lado, las

nuevas condiciones basales de los territorios, por ejemplo, la escasez de agua o contaminación, no permiten acceso directo al agua de los ecosistemas, como antaño. Los sistemas de conocimiento tradicionales se buscan reproducir en algunos territorios e iniciativas, pero no bajo una estrategia sistemática y articulada. Algunos ejemplos específicos que dan cuenta de esto es la eliminación de ecosistemas clave como humedales, o parches bioculturales como las huertas de Boca Sur para la instalación de proyectos inmobiliarios o viales como el Puente Industrial.

Como se adelanta en el Capítulo II, recuperar los vínculos orgánicos de las personas con la naturaleza se puede abordar desde una estrategia de restauración socio-ecológica. Entendiendo la relevancia de la dimensión política y la extensión histórica de la degradación en el área de estudio, se proponen líneas de restauración socio ecológica para reproducir un metabolismo socio-ecológico sano, las cuales se detallan a continuación.

i) Abordar los conflictos socioambientales, en particular el conflicto Mapuche, entendiendo que es la raíz del conflicto y una parte importante del conflicto forestal actual. En el informe final de la Comisión Presidencial para la Paz y el Entendimiento se analiza este tema en profundidad (Comisión Presidencial para la Paz y el Entendimiento, 2025). Se plantean la falta de reconocimiento, la pérdida histórica de tierras y la insuficiente respuesta a las demandas de reparación como las principales causas del conflicto entre el Estado y el pueblo Mapuche. Se destaca el rezago socioeconómico de las

regiones de Biobío, Araucanía, Los Ríos y Los Lagos, siendo las comunas más pobres de Chile. Se destaca el D.S. 701 y la creación de áreas silvestres protegidas como agravantes del conflicto. Se expone que la institucionalidad vigente (Ley Nº 19.253 de 1993 y la creación de la Corporación Nacional de Desarrollo Indígena (CONADI)) no da respuesta a los problemas actuales. Se presentan 21 recomendaciones, entre las cuales figura el reconocimiento constitucional y cultural del pueblo Mapuche, el acceso y control de tierras, y una convivencia territorial armónica entre el pueblo Mapuche y la industria forestal.

ii) Detener los forzantes de la degradación, a través de la regulación y control de las actividades extractivas intensivas, la cual es posible alcanzar mediante cuerpos legales como por ejemplo la Ley de Humedales o las NSCA. Así, se reconoce y se trabaja con el potencial intrínseco de la Naturaleza de sanarse a sí misma, cuando la degradación se detiene. Como se detalló en la Sección Cobertura/uso del suelo, hay limitaciones políticas para avanzar en este ítem.

iii) Preservar y restaurar las zonas de valor socio ecológico y parches bioculturales, entendiéndolas como zonas que reproducen un metabolismo socio ecológico que sostiene la integridad del sistema y donde residen los vínculos orgánicos de las personas con la naturaleza. La restauración socio ecológica implica una restauración multidimensional. En el ámbito económico, esto implica otorgar acceso y control sobre los ecosistemas y recursos, lo que

implica la posibilidad de generar ingresos con prácticas locales, lo que aborda el rezago socioeconómico en la zona con respecto al resto del país. Por ejemplo, en caletas, potenciar la pesca artesanal o la recolección algas de baja escala y no intensiva.

3.2. Integridad hidrológica

En las siguientes secciones se categoriza el Lago Lanalhue en un nivel de integridad asociado a dos variables: la temperatura y el nivel del agua. Este procedimiento es replicable para todos los sistemas lacustres, no obstante, es necesario contar con un estado de referencia del sistema, el cual, como fue explicado en la Sección 2. de esta discusión, se construyó sólo para el Lago Lanalhue. Las metodologías de teledetección, altimetría y modelación aquí desarrolladas podrían aplicarse a cualquier otro sistema lacustre, y en las siguientes secciones también se delinean algunas recomendaciones en su uso.

3.2.1. Temperatura del agua del lago

Para definir umbrales que separan estados deseables de indeseables, se puede recurrir al marco teórico de resiliencia de sistemas (G. J. A. Hansen et al., 2022).

El aumento de largo plazo de las temperaturas es un impacto del cambio climático ampliamente documentado, por lo que escogeremos un

umbral asociado a esto. El calentamiento progresivo encontrado en el Lago Lanalhue de 0.12ºC por década, se enmarca en un contexto global de calentamiento de lagos. A medida que la temperatura promedio global aumenta (0.15-0.20°C por década entre 1975 y 2009), la temperatura de los lagos muestra una tendencia al alza (0.34°C por década) (Kreakie et al., 2021). ¿Pero qué tendencia está asociada con un cambio no deseado de estado?

En estudios globales de lagos, se ha encontrado que se necesitarían en promedio 4.3°C para que un lago pase a un estado no deseado (G. J. A. Hansen et al., 2022). No obstante, los lagos de latitudes más bajas suelen tener resiliencia menor. Se calcula que cambios indeseados podrían ocurrir a los 2.4°C de calentamiento (Huang et al., 2024), por lo que se asociará ese umbral al estado de baja integridad. Asumiendo que la condición de referencia para la tendencia se sitúa en 1950, se obtiene una pendiente de 0.3ºC por década.

Como se mencionaba en la Sección 2. de esta discusión, en el Lago Lanalhue existe un calentamiento progresivo del agua de 0.12ºC/déc, con una tendencia más elevada en verano de 0.18ºC/déc, lo cual lo sitúa en un estado de integridad medio de acuerdo a este parámetro (ver Tabla VI.1). A medida que se incrementa la temperatura media del planeta (0,15–0,20 °C por década entre 1975 y 2009), las temperaturas lacustres muestran una tendencia ascendente de 0,34 °C por década (promedio global), con variaciones locales

asociadas a la heterogeneidad espacial del calentamiento (O'Reilly et al., 2015).

Con el propósito de mejorar la calidad de las aguas, hay varias medidas que pueden tomarse. Se ha encontrado globalmente, que la eutrofización y el aumento de la temperatura han sido los moduladores principales en la dinámica ecológica de los sistemas lacustres (G. J. A. Hansen et al., 2022; Luo et al., 2025). Los forzantes principales asociado a esto son la cobertura/uso del suelo y el cambio climático (Wu et al., 2025).

Por lo anterior, medidas de conservación y restauración que se proponen comúnmente tienen que ver con detener/controlar/moderar los forzantes de la degradación y hacer estos forzantes menos intensivos. Ejemplos son: i) Controlar los residuos (orgánicos y no orgánicos) que ingresan al cuerpo de agua. Los planes de descontaminación cuando se supera una NSCA apuntan principalmente a este aspecto (MMA, 2020). ii) La restauración de los 100-300m de riparia, entendiendo que son zonas críticas que influencian la calidad del agua (Zhu et al., 2024). iii) Aumentar el porcentaje de bosque nativo en la cuenca, lo cual mantiene la integridad biológica e hidrológica en cursos de agua y su calidad (Lee et al., 2023). iv) Medidas de adaptación climática, como hacer núcleos urbano multifuncionales (Korkou et al., 2023), atendiendo a la gran influencia que tienen los núcleos urbanos aledaños a los sistemas lacustres en

calentamientos urbanos locales y descarga de residuos urbanos (Cosgrove & Berkelhammer, 2018; Parra, 1989; Pedreros-Guarda et al., 2021).

La temperatura es uno de los varios parámetros físico-químicos que permiten determinar el estado de la calidad del agua de un sistema lacustre. Como hemos adelantado a lo largo de esta tesis doctoral, existen otros parámetros clave de calidad del agua como conductividad (µS/cm), pH (6,5–8,5), oxígeno disuelto (mg/l y % de saturación), turbidez (NTU), sílice (mg/l), demanda química de oxígeno (DQO) (mg/l), transparencia (m), nitrógeno total (mg/l), fósforo total (mg/l) y clorofila-a (µg/l), las que además se usan para aplicar las NSCA. Todos estos parámetros dan cuenta del grado trófico de un sistema lacustre, un marco teórico para evaluar estado. Varios de estos parámetros han sido obtenidos a partir de métodos similares al utilizado en el Capítulo III (Adjovu et al., 2023), lo que da cuenta de la potencial posibilidad de incorporar estas herramientas en la aplicación de NSCA, pero que requiere la toma de datos in-situ lo más cercano posible al paso de los satélites.

3.2.2. Nivel del agua del lago

El nivel del agua refleja el régimen hidrológico, como fue profundamente explicado en el Capítulo V. En el marco de la integridad ecológica, se ha definido el concepto de nivel del agua ecológico (NAE) del lago, que representa el nivel óptimo para mantener la integridad ecológica del sistema (proteger la biodiversidad, mejorar la calidad del ambiente y asegurar

estabilidad del sistema). Niveles menores destruirían la integridad ecológica del sistema (Yang et al., 2020).

De acuerdo a la metodología propuesta por (Yang et al., 2020), el NAE mínimo se calcula tradicionalmente como el nivel del agua (N) donde ocurre la máxima tasa de cambio del área (A) del lago, es decir, cuando se cumple la siguiente ecuación.

$$\frac{\partial^2 A(N)}{\partial^2 N} = 0$$

Si bien existen mejores formas para calcular hoy en día el NAE mínimo, considerando la vegetación presente en el sistema acuático (Yang et al., 2020), para el ejercicio operativo de esta discusión se usará el método tradicional.

En la Figure VI.1 se muestra la batimetría del Lago Lanalhue en 3D. Se puede observar lo irregular que es la batimetría del lago, con una zona somera al suroeste, una zona intermedia en la zona central del lago y una zona profunda en la zona norte.

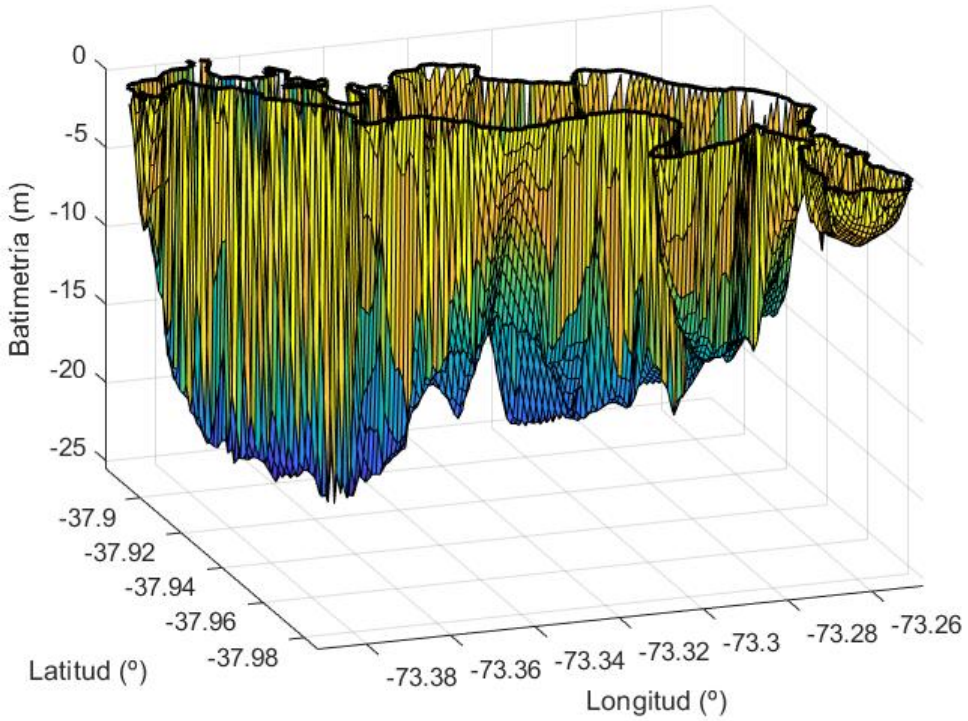


Figure VI.1. Batimetría 3D del Lago Lanalhue.

En base a la batimetría anterior, combinada con la topografía extraída de un modelo de elevación digital (DEM), primero se calcula A(N) (ver Figura 2a) para cada nivel (ver Capítulo V, Sección 3.3.3.). Se usa como referencia el nivel que había en el lago en 1950, en base al Capítulo V. Considerando la pendiente negativa de 5 mm por año, se proyecta que en 1950 había 37.5 cm más que el día que se tomó esta batimetría. Por lo tanto, se calcula el área desde el fondo hasta ese nivel, con un salto de 0.2 m. Segundo, se calcula $\partial A(N)/\partial N$ (ver Figura 2b). Tercero, se calcula $\partial^2 A(N)/\partial^2 N$ (ver Figura 2c).

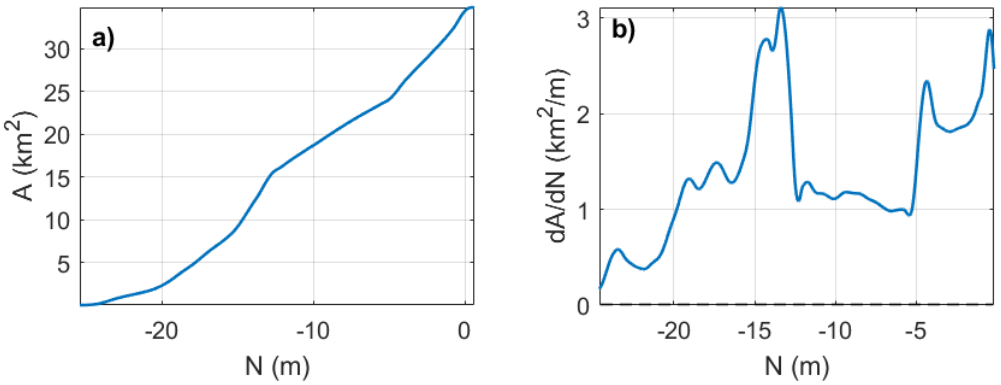


Figura VI.2. a) Area del lago (km^2) por nivel N (m). b) Derivada del área del lago con respecto a su nivel N.

En la Figura VI.2a se observa que el área empieza a aumentar desde el fondo hasta la superficie, naturalmente. En la Figura VI.2b, el primer máximo local alrededor del nivel -0.35 m podría estar indicando el NAE impuesto por el segmento somero del Lago Lanalhue, al suroeste (Figura 1b), cuya profundidad máxima es entre 5 y 6 m. En base a lo anterior, este NAE se fija como umbral que representa el paso de una integridad alta a baja. La segunda máxima pendiente ocurre a los -4.3 m de nivel, lo que estaría indicando la casi desaparición de la porción somera del lago. El aumento más rápido del área se observa alrededor de los 14 m de profundidad. Esto es evidenciado en la Figura 2b, que muestra la derivada de grado 1 más alta de A(N) con respecto al nivel (N). Este máximo podría estar indicando el un NAE sólo para la porción profunda del lago.

Se tomará como NAE mínimo los -0.35 m. Este nivel es con respecto al cero batimétrico, dato que fue tomado el 22 de Marzo del 2019. Eso quiere decir que el nivel del lago de ese día es el nivel cero en este análisis.

Entendiendo que la pendiente es de -5 mm por año, entre 1950 y 2025, el nivel del agua del lago ha disminuido 37.5 cm. Cabe destacar, que en la Figure V.7. Time series from 1950 to 2022, showing: 2-year (2-yr) window and long-term a) monthly i-s and retrieved (from WB Eq. (4)) lake water level, b) monthly accumulated precipitation from ERA5-L corrected with the long-term trend of ERA5 and TC (Section 4.1.2.). c) PDO, d) inverted AAO, and e) ENSO3.4 indices. Additionally, f) Global Warming index and g) long-term trend in linear lake evaporation are shown without 2-year window analysis.Figure V.7a, se observa que desde el 2000 hay una tendencia más pronunciada a la baja, la que se acentúa en 2010 con el inicio de la Megasequía en Chile-central. Esto se corresponde con la condición local de zona crítica de sequía a nivel mundial, de acuerdo al índice de sequía SPEI (standardized precipitation evapotranspiration index) (Beguería et al., 2023; Vicente-Serrano et al., 2010). La pendiente en este tramo tardío desde el 2000 es de -1 cm por año. Así, desde el 2019 hasta el 2025 se proyecta una disminución de 6 cm en el nivel del agua del lago. Es decir, desde el 2019 (el nivel cero), el NAE mínimo es -0.35 m, de los cuales se ha alcanzado el nivel -0.06 m.

Si bien este análisis muestra que el nivel del agua del Lago Lanalhue podría no haber superado niveles críticos de cantidad de agua, la batimetría original en 1950 es desconocida y eso cambiaría los resultados, al ser el NAE un parámetro que depende únicamente de la batimetría. Por lo anterior, se ha fijado un nivel de integridad alta aquella condición en la cual la disminución

histórica no supera los -0.35 m (NAE actual). La condición media se fija cuando la disminución histórica ya superó los -0.35 m, pero el nivel actual es mayor que el NAE (-0.35 m). Finalmente, el paso hacia un estado degradado o de baja integridad ocurre cuando el NAE se supera, reduciendo la integridad del lago, especialmente la porción somera.

Actualmente el Lago Lanalhue tiene una integridad media con respecto a este criterio, porque su nivel cambió históricamente 37,5 cm, pero no se ha superado la disminución (asociada al NAE) de 35 cm desde 2019. Si la condición seca se mantiene, y no se realizan acciones para adaptarse a esta nueva realidad climática, proyectando la pendiente de -1 cm por año, el NAE mínimo de -0.35 m se alcanzaría en el 2054, lo que marcaría el paso a un estado degradado del sistema lacustre, desde el punto de vista de la cantidad del agua.

Algunas iniciativas de restauración hidrológica de cuencas ampliamente usadas incluyen reforestación con bosque nativo en las zonas donde originalmente existían, restauración y conservación de humedales, restauración del buffer ripariano, restauración y conservación de la conectividad hidrológica, entre otros (Granata & Di Nunno, 2025; Meng et al., 2020).

La metodología desarrollada aquí del cálculo del NAE y los métodos para obtener niveles históricos del agua desarrollados en el Capítulo V son

altamente replicable a otros sistemas lacustres. En el Capítulo V se construyó el nivel del agua con ERA5-Land calibrada con datos meteorológicos in-situ y otras bases de datos hidroclimáticas. Estos datos son libres, por lo que se podría calibrar con estaciones meteorológicas cercanas a cualquier sistema lacustre. Además, se calibró el modelo hidrológico con datos altimétricos, presentes hoy en casi todos los cuerpos de agua con la misión SWOT. No obstante, en ausencia de datos altimétricos, o en el caso de tratarse de lagos muy pequeños, o si hay organización ciudadana en torno al sistema lacustre, es altamente recomendable usar mediciones in-situ, que pueden ser implementadas en el marco de un proyecto de ciencia ciudadana, como las experiencias presentadas en el Appendix V.I. Esto permite enmarcar el análisis de integridad en una estrategia de monitoreo participativo que tribute a otros propósitos como la educación, o la recuperación de vínculos entre las comunidades humanas y los ecosistemas.

4. Perspectivas de este trabajo

Bajo la perspectiva de esta tesis doctoral, el territorio es entendido como un sistema vivo y conceptualizado desde la definición de integridad ecológica descrita por Zelený et al. (2021): un sistema autoorganizado y autopoético, donde cada elemento cumple una función interconectada que sostiene la integridad ecológica del sistema entero. Ecológicamente, el bosque nativo regula el ciclo hidrológico permitiendo el flujo de agua durante

todo el año, incluso en los meses de verano. A través de los cursos de agua, se transportan nutrientes y organismos, contribuyendo a la fertilidad del paisaje y sosteniendo redes ecológicas. Los humedales, que se forman en zonas bajas de las cuencas, con inundaciones permanentes o estacionales, purifican el agua y sirven de refugio, reproducción y tránsito para muchas especies, incluidas aves migratorias. Los sistemas lacustres almacenan el agua y amortiguan desastres como sequías o inundaciones. El agua rica en nutrientes desemboca en el mar, alimentando el proceso de surgencia que ocurre en primavera y verano, donde los vientos permiten el ascenso de aguas profundas cargadas de nutrientes. Esto activa cadenas tróficas que comienzan con el fitoplancton y culminan en peces, moluscos, aves, mamíferos y seres humanos. Lo anterior ha sustentado históricamente la vida humana y hoy es parte del sustento de la economía de la zona costera de la región y de Chile.

El sistema socio ecológico actual, aunque degradado, mantiene una resiliencia sustentada por una compleja red de estructuras sociales, económicas, ecológicas y culturales: el trabajo, las formas de acceso al agua y los alimentos, los sistemas de conocimiento, la educación, etc. Pero esta resiliencia no reproduce un estado deseable: la desigualdad también es resiliente y se replica a sí misma (Fernández et al., 2016), es decir, es autopoiética.

Esta mirada, situada en la dinámica de ecosistemas, confirma fuertemente la necesidad de recurrir a un enfoque de restauración socio-ecológica, que cree estructuras multidimensionalmente que entreguen resiliencia a un estado deseable del sistema, más integro. No basta solo con restaurar, sino que es necesario darle sostenibilidad a la restauración. Que se reproduzca a sí misma sin asistencia humana. La restauración no puede reducirse a la plantación de árboles o a la compensación por daños ambientales, sino que debe reconocer y habilitar la capacidad de la naturaleza y de las comunidades para autoorganizarse, sanar y regenerarse. Este nuevo estado no replicará el pasado, pero podrá alcanzar una forma distinta de integridad, basada en la articulación de múltiples actores, incluyendo tanto comunidades indígenas como población urbana y rural no indígena, bajo un enfoque de restauración socio ecológica.

La definición de un estado íntegro requiere su conceptualización local (Westra & Lemons, 2012), es decir, puede haber conceptos distintos de qué es un estado íntegro dependiendo del lugar y el momento. En un territorio altamente degradado, un primer paso podría apuntar a recuperar la funcionalidad mínima. En nuestro caso, eso implicaría no tener problemas críticos como sequía, inundaciones y especialmente, mega incendios cada año. Pero nuevamente, la definición de estado íntegro y los resultados que se desean obtener con el manejo son conceptualizaciones que deben darse local y participativamente, tal como se plantea en la nueva Ley para la Naturaleza

(Biblioteca del Congreso Nacional, 2023), en el marco de la nueva institucionalidad para la gestión de las áreas protegidas de Chile mediante planes de manejo. En este contexto, la generación de indicadores como la presentada en esta tesis doctoral es un método operacional que acompaña y da seguimiento a los avances que se derivan de la gestión ambiental para alcanzar un estado deseable.

El marco teórico de integridad ecológica permite conceptualizar la degradación y la restauración desde un enfoque socio ecológico. Lo anterior permite evaluar el estado de la naturaleza con una mirada holística y ética, otorgándole un valor intrínseco a la naturaleza, cosmovisión que se asocia a un estado elevado de integridad.

Una característica importante de un sistema íntegro es la diversidad. La naturaleza tiende a la diversidad, y esa diversidad es una expresión de integridad, mientras que la homogeneidad conduce a la degradación. Ecosistemas diversos, como humedales, ríos, lagos, estuarios, bosques y glaciares, contribuyen al equilibrio de las cuencas, regulando el ciclo del agua, purificando naturalmente el recurso hídrico, sustentando biodiversidad, reduciendo riesgos como incendios o sequías, y mejorando tanto la calidad del aire como el bienestar humano. Las sociedades humanas, moldeadas por sus entornos ambientales, han desarrollado formas particulares de vida que deben ser consideradas y respetadas en cualquier proceso de restauración. En un mundo marcado por la homogeneización ecológica y cultural, restaurar

implica también diversificar. Por ello, la integridad ecológica está profundamente vinculada a la biodiversidad y a la diversidad cultural. De este modo, la integridad de un territorio se manifiesta tanto en su dimensión biofísica como en su gente, y la diversidad cultural representa la versión humana de la biodiversidad. Desde esta perspectiva, restaurar los territorios implica también restaurar los vínculos sociales, prácticas ancestrales y formas de habitar que han sido desplazadas o eliminadas por la expansión de modelos extractivistas y homogeneizantes.

Es clave trabajar con los recursos y capacidades disponibles hoy: academia, instituciones públicas, ciencia ciudadana, entre otros. Más allá de las limitaciones de este trabajo, uno de los principales desafíos identificados en ese ámbito es la desconexión entre los distintos sistemas de conocimiento (ciudadano, ancestral, académico) con la institucionalidad (Di Chiro, 2015). Este aislamiento impide que la ciencia académica y local se traduzca en mejoras concretas para los territorios y sus comunidades. Además, incluso las metodologías inter o transdiciplinarias pueden no recoger las voces locales y pueden tener remanentes de enfoques coloniales extractivistas. Desde ese lugar, no basta con que las metodologías alcancen estándares metodológicos, si no también éticos. Dependiendo del lugar, será más o menos necesario que las personas tomen mayor o menor liderazgo. Después de todo, muchos de los conocimientos que intentan integrarse en este nuevo pensamiento sistémico son conocimientos que ya existen a nivel local en diferentes partes

del mundo. Incorporar estos sistemas de conocimiento ancestrales y tradicionales en la institucionalidad ambiental puede fortalecer estructuras que repliquen un estado deseado de los sistemas socio-ecológicos.

En la línea del monitoreo y evaluación de estado de los sistemas socio ecológicos, existen nuevas formas emergentes de abordar las tareas. Un ejemplo es el validado en esta tesis: incorporar técnicas avanzadas de teledetección y modelación numérica. No obstante, estas herramientas requieren de validaciones con datos in-situ, lo que abre una oportunidad para alternativas al monitoreo in-situ. En este trabajo, se exploró la posibilidad de incorporar el marco teórico de monitoreo ciudadano/comunitario del agua en la gestión integrada del agua. Lo anterior constituye una vía concreta para enfrentar la desconexión entre sistemas de conocimiento local e institucional, y al mismo tiempo, abordar el déficit estructural de datos ambientales por escasez de recursos. Este tipo de convergencia permite democratizar el acceso al conocimiento, empoderar a las comunidades en la gestión de sus territorios y contribuir a la restauración desde una perspectiva colaborativa. Es una forma de generar estructuras que sostengan el nuevo estado del sistema al que queremos ir.

Esta exploración mencionada se desarrolló en el marco de proyectos comunitarios/ciudadanos de monitoreo de calidad y cantidad de agua, cuyas experiencias permiten enriquecer esta discusión y ampliar la mirada de este trabajo doctoral. Estos proyectos se detallan en los anexos: Appendix III.I y

Appendix V.I, donde se trabajó con varias organizaciones socio ambientales (Corporación Junquillar, Red de Humedales del Bíobío, Agrupación para la Conservación Laguna Antihuala, Agrupación Denavi Sur), entidades públicas (municipalidad de Cañete y San Pedro de la Paz, PRELA, Seremía de Medio Ambiente Región del Biobío) y entidades privadas (Llacolén) para incorporar a la región del Biobío un sistema de monitoreo participativo de la cantidad y calidad de agua. Este sistema es multipropósito, y sirve directamente como fuente de datos in-situ, así como también como datos que permiten validar tecnologías satelitales para la gestión hídrica, como por ejemplo información altimétrica.

En base a lo anterior, en este trabajo se formula una hipótesis emergente H4, que sostiene que el monitoreo ciudadano es una herramienta que puede fortalecer la gestión ambiental. Hoy existen muchos estudios que han desarrollado esta línea de investigación. Se ha abordado el valor que generan para la gestión, cualitativamente, mediante reportes de caso (Bonney et al., 2023; Simon et al., 2023); se ha relevado la costo-efectividad mediante el cálculo del costo y la precisión de los datos (Alfonso et al., 2022; Ardiantiono et al., 2025); se ha evaluado su efectividad mediante la comparación con datos satelitales (Kirby et al., 2021) o datos recolectados por profesionales (Albus et al., 2020). Así mismo, existen revisiones de las metodologías que se utilizan para la ciencia ciudadana (Shao & Bishop, 2025). La validación de la ciencia ciudadana puede ser abordada con cualquiera de los enfoques de

investigación mencionados y permite posicionarla e incorporarla formalmente en la aplicación de la legislación, como por ejemplo, la fiscalización.

En el marco del sistema de evaluación propuesto en esta tesis, el monitoreo ciudadano se entiende como un componente que fortalece principalmente las capacidades locales, aumentando la cantidad de datos a nivel temporal y espacial, y otorgando sostenibilidad del monitoreo de los ecosistemas. Permiten fortalecer las capacidades locales aumentando la cobertura de variables clave en periodos y lugares donde no existen mediciones sistemáticas. Además, permite apoyar a la investigación con ejercicios de validación de tecnologías (ej.: satélites) o reconstrucciones. Permite sostener procesos ciudadanos como educación ambiental, así como fortalecer el vínculo entre las personas y el territorio que habitan. Finalmente, permiten informar decisiones gestión y fiscalización. De este modo, la contribución de la ciencia ciudadana no se limita a casos aislados, sino que se integra como parte del desarrollo social y ambiental del territorio.

Estos enfoques abren prometedoras posibilidades de colaboración y sinergia profunda para abordar la degradación ambiental, cuyos aportes incluyen i) evaluaciones de conocimiento más integrales e integradoras; ii) una mayor comprensión mutua y confianza entre personas que se dedican a la gestión ambiental y otros actores clave; y (iii) soluciones que sean más ampliamente adoptadas y que se ajusten mejor a las condiciones locales (Fitchett et al., 2020).

Capítulo VII

Conclusiones generales

Esta tesis doctoral revela, desde un enfoque interdisciplinario y sistémico, la degradación del sistema costero–cordillera de Nahuelbuta, caracterizada por la pérdida de su integridad ecológica (en particular, natural/cultural e hidrológica). Este cambio es el resultado de procesos de larga duración (cinco siglos), modulados por una dimensión principalmente política, mediante el despojo, la ocupación de tierras y las políticas neoliberales. Los cambios se gestaron a partir de la colonización española en 1550, se profundizaron con la Ocupación de la Araucanía en 1881 y se intensificaron con la Dictadura militar desde 1973.

Se testean las hipótesis H1 y H2, que plantean que la ruptura del metabolismo socio ecológico produjeron alteraciones sustanciales a escala del paisaje, lo que sumado al cambio climático desigual, redujeron la integridad ecológica del paisaje y del agua en el sistema. Estas hipótesis son testeadas en los Capítulos II, III, IV y V, mediante cuatro variables clave: metabolismo socio ecológico, cobertura/uso del suelo, temperatura y nivel del agua del lago.

La cosmovisión mapuche, el sistema de conocimiento y el clima global en el estado de referencia sustentó prácticas humanas sostenibles y en sincronía con los ciclos estacionales, que reprodujeron una naturaleza abundante en recursos y accesible. Hoy, la cosmovisión dominante entiende la naturaleza como proveedora de bienes y servicios, lugar desde el cual se exacerbaron los usos extractivos e intensivos para promover el desarrollo económico, pero en desmedro del bienestar ecológico y social. Las consecuencias: la cobertura/uso del suelo pasó de ser en su mayoría bosque nativo a ser en su mayoría plantación forestal, quedando el bosque nativo reducido de 75 a 24% del territorio, y la plantación forestal aumentando de cero a la mitad.

La perturbación crónica a escala de paisaje combinada con el cambio climático global, pero desigual, que comienza a manifestarse en 1950, produjo una fractura en el ciclo hidrológico, que se manifiesta en el caso de estudio Lago Lanalhue, y se traduce en la disminución progresiva de la cantidad de agua, y la degradación de su calidad, evidenciado en el aumento progresivo de la temperatura del agua. Lo anterior da cuenta de la pérdida de integridad alta a media (en cuanto a temperatura y nivel del agua del Lago Lanalhue) o incluso baja (en cuanto al metabolismo socio-ecológico y cobertura/uso del suelo en todo el territorio), lo que sostiene la necesidad de generar acción inmediata y urgente, en especial en lo que concierne a la cobertura/uso del

suelo y el metabolismo socio-ecológico, las cuales modulan, junto con el clima, la temperatura y el nivel del agua de los lagos.

El cambio observado es estructural y multidimensional: social, cultural, ecológico, político, económico. Expresiones ecológicas graves y críticas de este cambio son los recientes megaincendios y las floraciones algales en sistemas lacustres.

Esta investigación representa una contribución en tres niveles. Primero, una contribución intelectual al campo interdisciplinario de las ciencias ambientales. En base a la articulación entre marcos teóricos (integridad ecológica, fractura antropogénica y monitoreo remoto del agua), innovaciones metodológicas y conocimiento local, se aporta al estado del arte del sistema costero – Cordillera de Nahuelbuta, y a la conceptualización de la degradación de la naturaleza desde una mirada sistémica, que va más allá de enfoques antropocéntricos y se sitúa desde el bienestar del sistema socio-ecológico completo, permitiendo incorporar el valor intrínseco que posee la naturaleza y su gente en la evaluación de estado.

Segundo, la investigación representa un aporte a la gestión ambiental, al operacionalizar el concepto de integridad ecológica, mostrando su utilidad para evaluar estados de referencia y actuales. Así, este trabajo consolida un paradigma de gestión ambiental que incorpora múltiples dimensiones de la degradación y ofrece flexibilidad para aplicarse en contextos de alta

vulnerabilidad. En base a las cuatro variables clave, se propone un sistema de evaluación de integridad ecológica con pertinencia a nivel local, nacional y latinoamericano. Esta propuesta se vincula con la realidad local: con instrumentos ambientales existentes (ej.: NSCA), con variables que ya se miden a nivel público (ej.: temperatura y nivel) y reconociendo la diversidad cultural presente en el territorio.

Tercero, permite acortar una brecha estructural de la gestión ambiental en Chile: la escasez de datos continuos, confiables y accesibles, con metodologías replicables en otros sistemas territoriales y humedales. Para otorgar pertinencia a la realidad económica local, se incluyen en su gran mayoría bases de datos de libre acceso (ej.: bases de datos hidro-climáticas, cartografías), herramientas avanzadas al servicio de la gestión ambiental (métodos de teledetección satelital, altimetría, y modelación hidrodinámica e hidrológica), pautas para incorporar la cosmovisión local (ej.: entrevistas cualitativas) y exploraciones al monitoreo ciudadano/participativo. Estas alternativas permitieron reconstruir los estados históricos y actuales de los sistemas acuáticos, y a la vez, contribuir a democratizar el conocimiento, el uso de tecnologías avanzadas y a la incorporación activa de la ciudadanía y el conocimiento local. Así, se aporta con una estrategia metodológica para el fortalecimiento y construcción de políticas de monitoreo y restauración socio-ecológica sostenibles. Esta contribución es lo que se buscaba testear con la

H3: validar herramientas de teledetección y modelación desarrolladas en los Capítulos III, IV y V.

Durante la ejecución de este trabajo, se plantea una hipótesis emergente, H4: el monitoreo ciudadano permite enriquecer y fortalecer la gestión ambiental. Esta hipótesis es explorada en extensiones transdisciplinarias de esta tesis doctoral de monitoreo ciudadano de calidad y cantidad de agua. Esto permite proyectar posibilidades para la restauración socio-ecológica en un territorio con comunidades ya involucradas con sus ecosistemas y comprometidas con su protección. Así mismo, permite proyectar una continuación de este trabajo con potencial de democratizar el acceso al conocimiento, empoderar a las comunidades en la gestión de sus territorios y contribuir a la restauración desde una perspectiva colaborativa.

Un entendimiento central que deja la tesis es la imposibilidad de recuperar la condición original, por lo cual la restauración debe orientarse hacia la creación de un nuevo estado de integridad socio-ecológica. Este nuevo horizonte se sustenta en la capacidad de los sistemas ecológicos y culturales de reproducirse y sostenerse autónomamente. En este marco, la restauración se convierte en un proceso de construcción de nuevas estructuras que repliquen el estado de integridad al que queremos ir, estructuras como sistemas de conocimiento, educación, institucionalidad, cuerpos legales, políticas públicas, prácticas de uso de la tierra, etc.

En segundo lugar, esta tesis concluye que la restauración requiere articular de manera efectiva la producción científica, la institucionalidad y la ciudadanía. Esto implica reconocer la dimensión política de la degradación y asumir la gobernanza como componente estructural de la restauración; orientar la investigación no solo por criterios metodológicos rigurosos, sino también por criterios éticos vinculados al resguardo de la integridad socio-ecológica; y situar la diversidad cultural y el conocimiento local como componentes habilitantes para construir estados íntegros. En consecuencia, el desafío no es solo democratizar el conocimiento científico, sino también incorporar de forma vinculante los saberes territoriales en la toma de decisiones y en el desarrollo científico.

Appendix VII.I: Cobertura/uso de suelo en cuencas de Lagos Nahuelbutanos.

Tabla VII.1: Cobertura y uso del suelo en 2019 para algunas de las Cuencas de los Lagos Nahuelbutanos, en porcentaje. Cartografía de CONAF (SIMEF, disponible en línea).

Cobertura/ uso del suelo	Grande	Chica	Posada-Junquillar	Quiñenco	Antihuala	Lanalhue	Lleulleu
1. Áreas urbanas e industriales	15,1	13,1	7,5	0,0	18,3	0,5	0,0

2. Terrenos agrícolas	0,4	0,0	0,7	1,2	14,5	7,3	5,7
3. Praderas y matorrales	3,8	3,6	8,9	9,5	9,7	7,3	13,2
4. Plantación forestal	49,8	46,4	70,0	70,6	35,6	42,8	53,8
5. Bosque nativo	6,2	4,0	9,6	14,5	14,7	28,1	17,8
6. Bosque mixto	10,5	17,1	0,8	1,3	2,7	2,2	1,3
7. Humedales	1,8	0,0	1,3	0,8	0,0	0,7	0,2
8. Áreas sin vegetación	0,0	0,0	0,0	0,0	0,2	0,1	0,1
9. Cuerpos de agua	12,4	0,2	1,0	2,2	4,3	9,2	6,9
Total uso antrópico intensivo (1, 2 y 4)	64,9	59,6	77,6	70,6	53,9	43,3	53,8

Appendix VII.II: Resumen de difusión

En el contexto de la crisis ecológica a nivel mundial, esta tesis analiza la degradación del sistema socio-ecológico de la Cordillera de Nahuelbuta y su zona costera, en el centro-sur de Chile, con especial foco en sus lagos,

llamados Lagos Nahuelbutanos. El objetivo principal es comprender cómo ha cambiado la integridad ecológica del sistema a lo largo del tiempo, comparando estados de referencia (precolombino, mediados del siglo XX y comienzos del siglo XXI) con actuales, para poder aportar conocimientos que permitan apoyar procesos de restauración socio-ecológica.

La integridad ecológica se entiende como la condición o estado de un ecosistema, considerando tanto sus componentes naturales como su relación con las personas. Para entender la evolución de la integridad, se analizaron cuatro variables principales.

En primer lugar, se reconstruyó la relación entre sociedad y naturaleza desde el año 1550 hasta la actualidad, a través de entrevistas a actores clave y revisión de antecedentes históricos. En segundo lugar, se estudiaron los cambios en la cobertura y uso del suelo, caracterizando la transición entre el estado de referencia y el actual. En tercer lugar, se analizó la temperatura superficial del agua de los lagos Nahuelbutanos con mayor foco en el Lago Lanalhue, como indicador de calidad del agua, utilizando imágenes satelitales y un modelo computacional. Finalmente, se evaluó el nivel del agua del Lago Lanalhue como indicador de cantidad de agua, mediante modelación hidrológica apoyada en datos satelitales. El foco en un lago: el Lanalhue, responde a la complejidad de los métodos, a la disponibilidad de datos para validar en este sistema, y a su relevancia en el marco de la generación de su norma secundaria de calidad ambiental.

Los resultados muestran pérdida de la integridad ecológica del sistema en todas las dimensiones estudiadas. En términos sociales, se observa una transición desde un sistema basado en el conocimiento tradicional, prácticas sustentables y acceso comunitario a los recursos naturales, hacia uno dominado por actividades extractivas intensivas, pérdida del conocimiento local y restricciones en el acceso a los ecosistemas, con alta privatización y fragmentación del territorio. Este cambio refleja una transformación profunda en la relación entre las personas.

En cuanto a la cobertura y uso del suelo, se identificó una reducción drástica del bosque nativo, que pasó de aproximadamente un 75% del territorio a solo un 24% en la actualidad. Este ha sido reemplazado principalmente por monocultivos forestales, que hoy representan cerca del 51% del área, además de agricultura y expansión urbana. Esta transformación del paisaje ha tenido consecuencias importantes sobre el funcionamiento de los ecosistemas, especialmente en el ciclo del agua, lo que se observa en los lagos.

En particular, en el caso de estudio Lago Lanalhue, se detectó un aumento sostenido en la temperatura del agua de aproximadamente 0,12 °C por década entre los años 2000 y 2024. Al mismo tiempo, se observó una disminución del nivel del agua de los lagos, con una reducción cercana a 5 centímetros por década desde 1950, lo que evidencia una pérdida progresiva de disponibilidad hídrica.

Para enfrentar estos resultados, la tesis propone una serie de métodos para el monitoreo y evaluación de los sistemas lacustres, utilizando herramientas tecnológicas avanzadas. Entre ellas se incluyen el uso de imágenes satelitales para estimar la temperatura del agua, modelos computacionales para simular el comportamiento térmico de los lagos y datos satelitales para medir niveles de agua. Estas metodologías mostraron altos niveles de precisión, lo que sugiere que pueden ser aplicadas en otros territorios. Asimismo, se destaca el potencial de integrar la ciencia ciudadana, incorporando el conocimiento local en los procesos de monitoreo ambiental.

El fortalecimiento de capacidades con tecnologías avanzadas se enmarca en un enfoque propuesto de restauración socio-ecológica, que implica, en primer lugar, abordar los conflictos socioambientales existentes, incluyendo las demandas y visiones de las comunidades locales. En segundo lugar, se requiere detener o controlar los factores que impulsan la degradación, como las prácticas de uso intensivo del suelo. Finalmente, es necesario avanzar en la conservación y restauración de áreas que presentan alto valor ecológico y social.

Referencias

Abarca-Del-Rio, R., CrÉtaux, J.-F., Berge-Nguyen, M., & Maisongrande, P. (2012). Does Lake Titicaca still control the Lake Poopó system water levels? An

investigation using satellite altimetry and MODIS data (2000–2009). *Remote Sensing Letters*, *3*(8), 707-714. https://doi.org/10.1080/01431161.2012.667884

Abarzúa et al. (2020). *Informe final: Análisis de Testigo Sedimentari... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Informe%20final%3A%20An%C3%A1lisis%20de%20Testigo%20Sedimentario%20en%20Lago%20Lanalhue%2C%20Provincia%20de%20Arauco%2C%20Regi%C3%B3n%20del%20Biob%C3%ADo&author=A.M.%20Abarz%C3%BAa&publication_year=2020

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, *5*(1), 170191. https://doi.org/10.1038/sdata.2017.191

Abubakar, H. B. (2024). *Evaluation of high-resolution precipitation datasets CHIRPS, TerraClimate and TAMSAT over the Enkangala Escarpment of South Africa*. Research Square. https://doi.org/10.21203/rs.3.rs-4365508/v1

Adjovu, G. E., Stephen, H., James, D., & Ahmad, S. (2023). Overview of the Application of Remote Sensing in Effective Monitoring of Water Quality Parameters. *Remote Sensing*, *15*(7), 1938. https://doi.org/10.3390/rs15071938

Afsharian, S., & Taylor, P. A. (2019). On the Potential Impact of Lake Erie Wind Farms on Water Temperatures and Mixed-Layer Depths: Some Preliminary 1-D Modeling Using COHERENS. *Journal of Geophysical Research: Oceans*, *124*(3), 1736-1749. https://doi.org/10.1029/2018JC014577

Agência Nacional de Águas. (2010). *NORMAS DE COBRANÇA PELO USO DE RECURSOS HÍDRICOS*. https://www.ana.gov.br/arquivos/institucional/sge/CEDOC/Catalogo/2010/NormasDeCobrancaPeloUsoDosRecursosHidricos2010.pdf

Agência Nacional de Águas e Saneamento Básico (ANA). (2025). *Qualidade da água*. https://www.gov.br/ana/pt-br/assuntos/monitoramento-e-eventos-criticos/qualidade-da-agua/qualidade-da-agua

Aguayo Arias, M. I. (2008). *El cambio de uso del suelo en el centro sur de Chile. Comprendiendo su dinámica a través de la modelación espacialmente explícita y explorando sus efectos ambientales en una cuenca hidrológica de meso escala.* [[PhD Thesis], Universidad de Concepción]. https://repositorio.udec.cl/handle/11594/6004

Aguayo, M., Pauchard, A., Azócar, G., & Parra, O. (2009). Cambio del uso del suelo en el centro sur de Chile a fines del siglo XX: Entendiendo la dinámica espacial y temporal del paisaje. *Revista chilena de historia natural*, *82*(3), 361-374.

Alaniz, A. J., Abarzúa, A. M., Martel-Cea, A., Jarpa, L., Hernández, M., Aquino-López, M. A., & Smith-Ramírez, C. (2021). Linking sedimentological and spatial analysis to assess the impact of the forestry industry on soil loss: The case of Lanalhue Basin, Chile. *CATENA*, *207*, 105660. https://doi.org/10.1016/j.catena.2021.105660

Alaniz, A. J., Smith-Ramírez, C., Rendón-Funes, A., Hidalgo-Corrotea, C., Carvajal, M. A., Vergara, P. M., & Fuentes, N. (2022). Multiscale spatial analysis of headwater vulnerability in South-Central Chile reveals a high threat due to deforestation and climate change. *Science of The Total Environment*, *849*,

157930. https://www.sciencedirect.com/science/article/pii/S004896972205029X

Albus, K. H., Thompson, R., Mitchell, F., Kennedy, J., & Ponette-González, A. G. (2020). Accuracy of long-term volunteer water monitoring data: A multiscale analysis from a statewide citizen science program. *PLOS ONE*, *15*(1), e0227540. https://doi.org/10.1371/journal.pone.0227540

Alfonso, L., Gharesifard, M., & Wehn, U. (2022). Analysing the value of environmental citizen-generated data: Complementarity and cost per observation. *Journal of Environmental Management*, *303*, 114157. https://doi.org/10.1016/j.jenvman.2021.114157

Allan, M. G., Hamilton, D. P., Trolle, D., Muraoka, K., & McBride, C. (2016). Spatial heterogeneity in geothermally-influenced lakes derived from atmospherically corrected Landsat thermal imagery and three-dimensional hydrodynamic modelling. *International Journal of Applied Earth Observation and Geoinformation*, *50*, 106-116. https://doi.org/10.1016/j.jag.2016.03.006

Almanza, V., Parra, O., De M. Bicudo, C. E., Baeza, C., Beltran, J., Figueroa, R., & Urrutia, R. (2016). Occurrence of toxic blooms of Microcystis aeruginosa in a central Chilean (36° Lat. S) urban lake. *Revista Chilena de Historia Natural*, *89*(1), 8. https://doi.org/10.1186/s40693-016-0057-7

Altieri, M. A., & Rojas, A. (1999). Ecological Impacts of Chile's Neoliberal Policies, with Special Emphasis on Agroecosystems. *Environment, Development and Sustainability*, *1*(1), 55-72.

Altman, D. G. (1990). *Practical Statistics for Medical Research*. Chapman and Hall/CRC. https://doi.org/10.1201/9780429258589

Alvial Vásquez, F.-J., Abarca-del-Río, R., & Ávila, A. I. (2020). High-Resolution Precipitation Gridded Dataset on the South-Central Zone (34° S–41° S) of Chile. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.519975

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M., Moghaddam, S. H. A., Mahdavi, S., Ghahremanloo, M., Parsian, S., Wu, Q., & Brisco, B. (2020). Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 5326-5350. https://doi.org/10.1109/JSTARS.2020.3021052

Amour, I., & Kauranne, T. (2017). A variational ensemble Kalman filtering method for data assimilation using 2D and 3D version of COHERENS model. *International Journal for Numerical Methods in Fluids*, *83*(6), 544-558. https://doi.org/10.1002/fld.4276

Angrosino, M. (2012). *Etnografía y observación participante en Investigación Cualitativa*. Ediciones Morata.

Araos, F., Catalán, E., Nuñez, D., Riquelme, W., Cortinez, V., de Fina, D., & Anbleyth-Evans, J. (2023). Cuidando la Patagonia Azul: Prácticas y estrategias de los pueblos originarios para curar las zonas marinas del sur de Chile. *The Journal of Latin American and Caribbean Anthropology*, *28*(4), 286-297. https://onlinelibrary.wiley.com/doi/abs/10.1111/jlca.12695

Araya. (2019). *Desafíos del turismo y la conservación de la biodiversidad* (Primera edición, septiembre de 2019). Amukan Editorial itinerante.

Ardiantiono, Deere, N. J., Seaman, D. J. I., Mamat Rahmat, U., Ramadiyanta, E., Lubis, M. I., Trihangga, A., Yasin, A., Alza, G., Sari, D. P., Daud, M., Abdullah, R., Mutia, R., Melvern, D., Tarmizi, Supriatna, J., & Struebig, M. J. (2025).

Improved cost-effectiveness of species monitoring programs through data integration. *Current Biology*, *35*(2), 391-397.e3. https://doi.org/10.1016/j.cub.2024.11.051

Argyilan, E. P., & Forman, S. L. (2003). Lake Level Response to Seasonal Climatic Variability in the Lake Michigan-Huron System from 1920 to 1995. *Journal of Great Lakes Research*, *29*(3), 488-500. https://doi.org/10.1016/S0380-1330(03)70453-5

Aróstegui, M. G. (2001). Cultura de la resistencia. Concepciones teóricas y metodológicas para su estudio. *Islas*, (127), 20-41. http://islas.uclv.edu.cu/index.php/islas/article/download/721/646

Arroyo, M. T. K. (2006). *El hotspot chileno, prioridad mundial para la conservación. Diversidad de ecosistemas, ecosistemas terrestres*.

Arsen, A., Crétaux, J.-F., Berge-Nguyen, M., & Del Rio, R. A. (2014). Remote Sensing-Derived Bathymetry of Lake Poopó. *Remote Sensing*, *6*(1), 407-420. https://doi.org/10.3390/rs6010407

Ascencio, E., Rivera, P., Cruces, F., Vila, I., Ascencio, E., Rivera, P., Cruces, F., & Vila, I. (2018). Estudio morfológico de Naiadinium polonicum (Dinophyceae) reportado por primera vez en aguas continentales de Chile. *Gayana. Botánica*, *75*(1), 438-446. https://doi.org/10.4067/S0717-66432018000100438

Assumpção, T. H., Popescu, I., Jonoski, A., & Solomatine, D. P. (2018). Citizen observations contributing to flood modelling: Opportunities and challenges. *Hydrology and Earth System Sciences*, *22*(2), 1473-1489. https://doi.org/10.5194/hess-22-1473-2018

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., Van Den Hurk, B., Hirschi, M., & Betts, A. K. (2009). A Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System. *Journal of Hydrometeorology*, *10*(3), 623-643. https://doi.org/10.1175/2008JHM1068.1

Banco Central de Chile. (2025). *Base de Datos Estadísticos (BDE)*. https://si3.bcentral.cl/siete/ES/Siete/Cuadro/CAP_CCNN/MN_CCNN76/CCNN_EP18_05_ratio

Baracchini, T., Hummel, S., Verlaan, M., Cimatoribus, A., Wüest, A., & Bouffard, D. (2020). An automated calibration framework and open source tools for 3D lake hydrodynamic models. *Environmental Modelling & Software*, *134*, 104787. https://doi.org/10.1016/j.envsoft.2020.104787

Barría, P., Chadwick, C., Ocampo-Melgar, A., Galleguillos, M., Garreaud, R., Díaz-Vasconcellos, R., Poblete, D., Rubio-Álvarez, E., & Poblete-Caballero, D. (2021). Water management or megadrought: What caused the Chilean Aculeo Lake drying? *Regional Environmental Change*, *21*(1), 19. https://doi.org/10.1007/s10113-021-01750-w

Barros Delgado, B. B. J. (2022). *Dinámica de los asentamientos rurales y su relación con la expansión forestal en las comunas de Curanilahue, Lebu y Los Álamos, entre el periodo 1960—2002*. https://repositorio.uchile.cl/handle/2250/188639

Batina, A., & Krtalić, A. (2024). Integrating Remote Sensing Methods for Monitoring Lake Water Quality: A Comprehensive Review. *Hydrology*, *11*(7), 92. https://doi.org/10.3390/hydrology11070092

BCN. (2024). *Biblioteca del Congreso Nacional de Chile. Glosario de términos geográficos*. https://www.bcn.cl/siit/glosario/index_html

BCNa. (2024). *Reporte Comunal—Biblioteca del Congreso Nacional de Chile*. https://www.bcn.cl/siit/reportescomunales/comunas_v.html?anno=2023&idcom=8108

BCNb. (2017). *Buscador Estadístico—SIIT*. https://www.bcn.cl/siit/estadisticasterritoriales//resultados-consulta?id=326233

BCNc. (2024). *Chile: Población censada y tasas de crecimiento medio anual, según ciudades, 1950-2002*. https://www.memoriachilena.gob.cl/602/w3-article-74944.html

Beguería, S., Vicente Serrano, S. M., Reig-Gracia, F., & Latorre Garcés, B. (2023). *SPEIbase v.2.9 [Dataset]* [Dataset]. DIGITAL.CSIC. https://doi.org/10.20350/digitalCSIC/15470

Belete, M. D., Diekkrüger, B., & Roehrig, J. (2017). Linkage between Water Level Dynamics and Climate Variability: The Case of Lake Hawassa Hydrology and ENSO Phenomena. *Climate*, *5*(1), 21. https://doi.org/10.3390/cli5010021

Bengoa, J. (2000). *Historia del pueblo mapuche: (Siglo XIX y XX)*. Lom Ediciones.

Bengtsson, L. (2012). Water Balance of Lakes. En L. Bengtsson, R. W. Herschy, & R. W. Fairbridge (Eds.), *Encyclopedia of Lakes and Reservoirs* (pp. 863-864). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4410-6_18

Betts, A. K., Reid, D., & Crossett, C. (2020). Evaluation of the FLake Model in ERA5 for Lake Champlain. *Frontiers in Environmental Science*, *8*. https://doi.org/10.3389/fenvs.2020.609254

Beutel, M. W., Horne, A. J., Roth, J. C., & Barratt, N. J. (2001). Limnological effects of anthropogenic desiccation of a large, saline lake, Walker Lake, Nevada. *Hydrobiologia*, *466*(1), 91-105. https://doi.org/10.1023/A:1014569521381

Biblioteca del Congreso Nacional. (2021, octubre 13). *Biblioteca del Congreso Nacional | Ley Chile*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Biblioteca del Congreso Nacional. (2023, septiembre 6). *Ley 21600 CREA EL SERVICIO DE BIODIVERSIDAD Y ÁREAS PROTEGIDAS Y EL SISTEMA NACIONAL DE ÁREAS PROTEGIDAS*. www.bcn.cl/leychile. https://www.bcn.cl/leychile

Bio Bio (Director). (2023, febrero 13). *Dichos de Boric por regulación de industria forestal fueron catalogados como «fuera de contexto»* [Video recording]. https://www.youtube.com/watch?v=do0zHOXR5Us

Bolados, P., Espinoza, L., & Panez, A. (2024). Una aproximación decolonial a las Zonas de Sacrificio en Chile. *Vibrant: Virtual Brazilian Anthropology*, *21*, e21603. https://www.scielo.br/j/vb/a/vtQ6tPk9TWjThNfhNJTLtcv/?lang=es

Bongioannini Cerlini, P., Saraceni, M., Silvestri, L., Meniconi, S., & Brunone, B. (2022). Monitoring the Water Mass Balance Variability of Small Shallow Lakes by an ERA5-Land Reanalysis and Water Level Measurement-Based Model. An Application to the Trasimeno Lake, Italy. *Atmosphere*, *13*(6), Article 6. https://doi.org/10.3390/atmos13060949

Bonney, P. R., Hansen, B. D., & Baldwin, C. (2023). Citizen Science and Natural Resource Management: A Social Network Analysis of Two Community-Based Water Monitoring Programs. *Society & Natural Resources*, *36*(6), 600-621. https://doi.org/10.1080/08941920.2023.2183445

Boy, F., Crétaux, J.-F., Boussaroque, M., & Tison, C. (2022). Improving Sentinel-3 SAR Mode Processing Over Lake Using Numerical Simulations. *IEEE*

Transactions on Geoscience and Remote Sensing, *60*, 1-18. https://doi.org/10.1109/TGRS.2021.3137034

Bravo Ferretti, C., Sandoval-Díaz, J., Astudillo Pizarro, F., Bravo Ferretti, C., Sandoval-Díaz, J., & Astudillo Pizarro, F. (2022). Narrativas del acorralamiento. Identidad de Lugar en la Bahía de Coronel a partir de la reconversión productiva. *Revista de historia (Concepción)*, *29*(1), 73-105. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-88322022000100073&lng=es&nrm=iso&tlng=en

Bravo Orrego, C. M. (2018). *Caracterización de la precipitación en la Cordillera de Nahuelbuta según la microfísica bajo la cual ocurre* [[PhD Thesis], Universidad de Chile]. https://repositorio.uchile.cl/handle/2250/168171

Brown, C. F., Brumby, S. P., Guzder-Williams, B., Birch, T., Hyde, S. B., Mazzariello, J., Czerwinski, W., Pasquarella, V. J., Haertel, R., Ilyushchenko, S., Schwehr, K., Weisse, M., Stolle, F., Hanson, C., Guinan, O., Moore, R., & Tait, A. M. (2022). Dynamic World, Near real-time global 10 m land use land cover mapping. *Scientific Data*, *9*(1), 251. https://www.nature.com/articles/s41597-022-01307-4

Budds, J. (2013). Water, Power, and the Production of Neoliberalism in Chile, 1973–2005. *Environment and Planning D: Society and Space*, *31*(2), 301-318. https://doi.org/10.1068/d9511

Burić, D., & Penjišević, I. (2023). Southern Hemisphere temperature trend in association with greenhouse gases, El Niño Southern Oscillation, and Antarctic Oscillation. *Időjárás*, *127*(1), 23-42. https://doi.org/10.28974/idojaras.2023.1.2

Burns, N. (2020). *Protocol for Monitoring Trophic Levels of New Zealand Lakes and Reservoirs*.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, *2*. https://www.frontiersin.org/articles/10.3389/feart.2014.00026

Carlson, R. E. (1977). A trophic state index for lakes. *Limnology and Oceanography*, *22*(2), 361-369. https://doi.org/10.4319/lo.1977.22.2.0361

Carmona, A., & Nahuelhual, L. (2012). Combining land transitions and trajectories in assessing forest cover change. *Applied Geography*, *32*(2), 904-915. https://www.sciencedirect.com/science/article/pii/S0143622811001755

Caro, C. S. M. (2003). *Aproximación a las estrategias de sobrevivencia de las familias de la caleta de Boca Sur Viejo en San Pedro de la Paz; experiencia y estudio de caso* [[PhD Thesis]]. Universidad de Concepción.

Carrasco Henríquez, N., & Mendoza Leal, C. (2021). Restoration as a re-commoning process. Territorial initiative and global conditions in the process of water recovery in the 'Cordillera de Nahuelbuta', Chile. *Ecosystems and People*, *17*(1), 556-573. https://doi.org/10.1080/26395916.2021.1993345

Castillo, S. F. (s. f.). *Ciudad y el derecho al buen vivir: Contribución rural a la reconstrucción de espacios fragmentados Barrio Boca Sur, Concepción, Chile.*

Chazdon, R. L., Falk, D. A., Banin, L. F., Wagner, M., J. Wilson, S., Grabowski, R. C., & Suding, K. N. (2024). The intervention continuum in restoration ecology: Rethinking the active–passive dichotomy. *Restoration Ecology*, *32*(8), e13535. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.13535

Cheng, C., Du, W., Li, J., Bao, A., Ge, W., Wang, S., Ma, D., & Pan, Y. (2023). Spatiotemporal Variations of Glacier Mass Balance in the Tomur Peak Region Based on Multi-Source Altimetry Remote Sensing Data. *Remote Sensing*, *15*(17), 4143. https://doi.org/10.3390/rs15174143

Cheng, C., Xing, Z., Ye, L., Yang, J., & Xie, Z. (2024). Characteristics and Influencing Factors of Landscape Pattern Gradient Transformation of Small-Scale Agroforestry Patches in Mountain Cities. *Sustainability*, *16*(15), 6322. https://doi.org/10.3390/su16156322

Chicco, D., Warrens, M. J., & Jurman, G. (2021). The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Computer Science*, *7*, e623. https://doi.org/10.7717/peerj-cs.623

Chile_ING_ESP.xls. (s. f.). Recuperado 25 de julio de 2025, de https://www.memoriachilena.gob.cl/archivos2/pdfs/MC0018840.PDF

Choongik, C. (2025). Unequal Distribution of Climate Change Impacts across Regions: Towards Climate Justice. *Journal of Distribution Science*, *23*(4), 103-116. https://koreascience.kr/article/JAKO202512250404430.page

Choukrani, H., Lacombe, G., Zwarteveen, M., Kuper, M., Taky, A., & Hammani, A. (2023). Sense-making and shaping of temporary wetlands: A socio-hydrological analysis of dichotomous ontologies of merjas in Morocco. *Journal of Hydrology*, 130434. https://doi.org/10.1016/j.jhydrol.2023.130434

Clark, B., & York, R. (2008). Rifts and Shifts: Getting to the Root of Environmental Crises. *Monthly Review*, *60*(6), 13. http://archive.monthlyreview.org/index.php/mr/article/view/MR-060-06-2008-10_2

Clark, N. E., Eber, L. E., Laurs, R. M., Renneer, J. A., & Saur, J. F. T. (1974). *Heat exchange between ocean and atmosphere in the eastern North Pacific for 1961-71*. https://repository.library.noaa.gov/view/noaa/11864/noaa_11864_DS1.pdf

Clark, & York. (2005). Carbon metabolism: Global capitalism, climate change, and the biospheric rift. *Theory and Society*, *34*(4), 391-428. https://doi.org/10.1007/s11186-005-1993-4

CNES. (2015). *How altimetry works [online]. Toulouse, Centre national d'études spatiales (CNES)*. https://cnes.fr/en/how-altimetry-works

Comisión Presidencial para la Paz y el Entendimiento. (2025). *Resumen ejecutivo de las recomendaciones al Estado de Chile en materia de tierras y derechos del pueblo Mapuche*. Ministerio Secretaría General de la Presidencia. https://www.comisionpazyentendimiento.gob.cl/wp-content/uploads/2025/05/Resumen-Ejecutivo-Oficial-Cierre-Comision-para-la-Paz-y-el-Entendimiento.pdf

Condom, T., Martínez, R., Pabón, J. D., Costa, F., Pineda, L., Nieto, J. J., López, F., & Villacis, M. (2020). Climatological and Hydrological Observations for the South American Andes: In situ Stations, Satellite, and Reanalysis Data Sets. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.00092

Congalton, R. G., Gu, J., Yadav, K., Thenkabail, P., & Ozdogan, M. (2014). Global Land Cover Mapping: A Review and Uncertainty Analysis. *Remote Sensing*, *6*(12), 12070-12093. https://doi.org/10.3390/rs61212070

COPERNICUS. (2025). *Land Monitoring Service: Temperature and Reflectance*. https://land.copernicus.eu/en/products/temperature-and-reflectance

Corporación Junquillar. (2024). *Protocolo de monitoreo de calidad del agua en la Laguna Junquillar*.

Corporación Junquillar. (2025). *Laguna Junquillar (@lagunajunquillar) • Fotos y videos de Instagram*. https://www.instagram.com/lagunajunquillar/

Correa, M. (2021). La Historia del Despojo; El Origen de la Propiedad Particular en el Territorio. *Santiago, Chile: Ceibo-Pehuén Ediciones*.

Cosgrove, A., & Berkelhammer, M. (2018). Downwind footprint of an urban heat island on air and lake temperatures. *Npj Climate and Atmospheric Science*, *1*(1), 46. https://doi.org/10.1038/s41612-018-0055-3

(CR)2. (2025). *Explorador climático (CR)2* (Available online) [Dataset]. https://explorador.cr2.cl/

Cretaux, J., Kouraev, A., Papa, F., Bergé-Nguyen, M., Cazenave, A., Aladin, N., & Plotnikov, I. (2005). *Water balance of the Big Aral Sea from satellite remote sensing and in situ observations*. *31*.

Crétaux, J.-F., Abarca-del-Río, R., Bergé-Nguyen, M., Arsen, A., Drolon, V., Clos, G., & Maisongrande, P. (2016). Lake Volume Monitoring from Space. *Surveys in Geophysics*, *37*(2), 269-305. https://doi.org/10.1007/s10712-016-9362-6

Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011a). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., & Maisongrande, P. (2011b). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, *47*(9), 1497-1507. https://doi.org/10.1016/j.asr.2011.01.004

Crétaux, J.-F., & Birkett, C. (2006). Lake studies from satellite radar altimetry. *Comptes Rendus Geoscience, La Terre observée depuis l'espace*, *338*(14), 1098-1112. https://doi.org/10.1016/j.crte.2006.08.002

CTOH. (2024, julio 10). *Altimetric Time Series Software (AITiS) [software]*. GitLab. https://gitlab.com/ctoh/altis

Cuomo, C. J. (2011). Climate change, vulnerability, and responsibility. *Hypatia*, *26*(4), 690-714.

Da Silva, J. S., Seyler, F., Calmant, S., Rotunno Filho, O. C., Roux, E., Araújo, A. A. M., & Guyot, J. L. (2012). Water level dynamics of Amazon wetlands at the watershed scale by satellite altimetry. *International Journal of Remote Sensing*, *33*(11), 3323-3353. https://doi.org/10.1080/01431161.2010.531914

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018a). Understanding the abrupt climate change in the mid-1970s from a phase-space transform perspective. *Journal of Applied Meteorology and Climatology*, *57*(11), 2551-2560. https://journals.ametsoc.org/view/journals/apme/57/11/jamc-d-17-0345.1.xml

Dai, T., Dong, W., Guo, Y., Hong, T., Ji, D., Yang, S., Tian, D., Wen, X., & Zhu, X. (2018b). *Understanding the Abrupt Climate Change in the Mid-1970s from a Phase-Space Transform Perspective*. https://doi.org/10.1175/JAMC-D-17-0345.1

Davidson, N. C., Fluet-Chouinard, E., & Finlayson, C. M. (2018). Global extent and distribution of wetlands: Trends and issues. *Marine and Freshwater Research*, *69*(4), 620-627. https://www.publish.csiro.au/mf/MF17019

Delgado, F., & Rist. (2016). *Las ciencias desde la perspectiva del diálogo de saberes, la transdisciplinariedad y el diálogo intercientífico*.

Deltares. (2025). *Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments User Manual Hydro-Morphodynamics Version: 4.05.* https://www.google.com/search?q=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&oq=Deltares+(2025).+Simulation+of+multi-dimensional+hydrodynamic+flows+and+transport+phenomena%2C+including+sediments+User+Manual+Hydro-Morphodynamics+Version%3A+4.05.+Delatares.&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBBzQxOWowajSoAgCwAgE&sourceid=chrome&ie=UTF-8

DGA. (2025a). *Red hidrométrica en línea DGA.* [Dataset]. https://dga.mop.gob.cl/servicioshidrometeorologicos/Paginas/default.aspx

DGA. (2025b). *Sistema Hidrométrico en Línea | Dirección General de Aguas*. https://dga.mop.gob.cl/sistema-hidrometrico-en-linea/

Di Chiro, G. (2015). A New Spelling Of Sustainability: Engaging Feminist-Environmental Justice Theory And Practice. *Practising Feminist Political Ecologies: Moving Beyond The «Green Economy»*, 211-236. https://doi.org/10.5040/9781350221970.ch-007

Echeverría, C., Bolados, G., Rodriguez, J., Aguayo, M., & Premoli, A. (s. f.). Ecología de Paisajes Forestales. *2014*.

ECMWF. (2020). *ECMWF Confluence Wiki: 3.3. OpenIFS: Surface Model HTESSEL [online]. Reading, European Centre for Medium-Range Weather Forecasts (ECMWF).* https://confluence.ecmwf.int/display/OIFS/3.3+OpenIFS%3A+Surface+Model+HTESSEL

ECMWF. (2025). *ERA5: Data documentation—Copernicus Knowledge Base—ECMWF Confluence Wiki*. https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation

ECMWF/C3S. (2024a). *Earth Engine Data Catalog: ERA5 Monthly Aggregates [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_MONTHLY#bands

ECMWF/C3S. (2024b). *Earth Engine Data Catalog: ERA5-Land Monthly Aggregated [online].* https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR

ECOMOD. (2025). *COHERENS modelling system. ECOMOD – Marine Ecosystem Modelling*. https://ecomod.be/projects/COHERENS/

EEDC. (2025a). *USGS Landsat 8 Level 2, Collection 2, Tier 1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

EEDC. (2025b). *WorldClim Climatology V1 | Earth Engine Data Catalog*. Google for Developers. https://developers.google.com/earth-engine/datasets/catalog/WORLDCLIM_V1_MONTHLY?hl=es-419

EEDCa. (2025). *USGS Landsat 8 Collection 2 Tier 1 and Real-Time data Raw Scenes* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_RT?hl=es-419

EEDCb. (2025). *USGS Landsat 8 Collection 2 Tier 1 TOA Reflectanc* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_TOA?hl=es-419

EEDCc. (2025). *USGS Landsat 8 Level 2, Collection 2, Tier 1* [Dataset]. https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2?hl=es-419

Elachi, C., & Van Zyl, J. J. (2006). Introduction to the physics and techniques of remote sensing. John Wiley and Sons. *New Jersey. USA 513p*.

Elachi, C., & Zyl, J. J. van. (2021). *Introduction to the Physics and Techniques of Remote Sensing*. John Wiley & Sons.

EMOL, E. M. (2023, febrero 13). *Monsalve y debate abierto por Boric sobre industria forestal: «Sería irracional que la sociedad no diera una discusión»*. Emol. https://www.emol.com/noticias/Nacional/2023/02/13/1086588/monsalve-industria-forestal.html

EROS. (2022, noviembre 9). *USGS EROS Archive—Landsat Archives—Landsat 8-9 OLI/TIRS Collection 2 Level-2 Science Products | U.S. Geological Survey*. https://www.usgs.gov/centers/eros/science/usgs-eros-archive-landsat-archives-landsat-8-9-olitirs-collection-2-level-2

ESA. (2025a). *ATSR Reprocessing for Climate: Lake Surface Water Temperature & Ice Cover (ARC-Lake)*. https://datashare.ed.ac.uk/handle/10283/88

ESA. (2025b). *Summary of RESETlakes (REmote SEnsing of Tipping points in Lakes)*. ESA Climate Office. https://climate.esa.int/en/tipping-points-research/about-resetlakes/about-resetlakes/

European Environment Agency. (2018, julio 3). *Quality element status*. https://www.eea.europa.eu/en/analysis/maps-and-charts/quality-elements-of-water-bodies-water-assessments

Falkenmark, M., & Rockström, J. (2004). *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. Earthscan.

Falvey, M., & Garreaud, R. D. (2009). Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). *Journal of Geophysical Research: Atmospheres*, *114*(D4). https://doi.org/10.1029/2008JD010519

Fang, G. H., Yang, J., Chen, Y. N., & Zammit, C. (2015). Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, *19*(6), 2547-2559. https://doi.org/10.5194/hess-19-2547-2015

Fang, X., & An, D. (2022). Evaluation on sea surface wind speed product of Fengyun-3D satellite microwave radiation imager using ERA-5 dataset. *International Journal of Remote Sensing*, *43*(10), 3671-3691. https://doi.org/10.1080/01431161.2022.2099770

Fang, X., & Stefan, H. G. (1996). Dynamics of heat exchange between sediment and water in a lake. *Water Resources Research*, *32*(6), 1719-1727. https://doi.org/10.1029/96WR00274

FAO. (2025). *NEW! Check out the Open Foris interactive story*. OpenForis. https://www.fao.org/in-action/openforis/en

Farnaz Nojavan, F. N., Kreakie, B. J., Hollister, J. W., & Qian, S. S. (2019). Rethinking the lake trophic state index. *PeerJ*, *7*, e7936. https://doi.org/10.7717/peerj.7936

Fatichi, S. (2025, agosto 1). *Mann-Kendall Test (https://www.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test), MATLAB Central File Exchange. Recuperado 1 agosto, 2025.* https://la.mathworks.com/matlabcentral/fileexchange/25531-mann-kendall-test

Fernández, I. C., Manuel-Navarrete, D., & Torres-Salinas, R. (2016). Breaking resilient patterns of inequality in Santiago de Chile: Challenges to navigate towards a more sustainable city. *Sustainability*, *8*(8), 820. https://www.mdpi.com/2071-1050/8/8/820

Fernández-Manjarrés, J. F., Roturier, S., & Bilhaut, A.-G. (2018). The emergence of the social-ecological restoration concept. *Restoration Ecology*, *26*(3), 404-410. https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.12685

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302-4315. https://doi.org/10.1002/joc.5086

Fischer, R., Tamayo Cordero, F., Ojeda Luna, T., Ferrer Velasco, R., DeDecker, M., Torres, B., Giessen, L., & Günter, S. (2021). Interplay of governance elements and their effects on deforestation in tropical landscapes: Quantitative insights from Ecuador. *World Development*, *148*, 105665. https://www.sciencedirect.com/science/article/pii/S0305750X21002801

Fitchett, L. L., Sorice, M. G., Cobourn, K. M., Boyle, K. J., Klug, J. L., & Weathers, K. C. (2020). Pathways to enhanced lake integrity: A Framework to assess the effectiveness of local lake associations. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *25*(2), 258-268. https://doi.org/10.1111/lre.12308

Flavelle, A. (2003). *Mapping Our Land: Community Mapping Handbook*. Lone Pine.

Fluet-Chouinard, E., Stocker, B. D., Zhang, Z., Malhotra, A., Melton, J. R., Poulter, B., Kaplan, J. O., Goldewijk, K. K., Siebert, S., Minayeva, T., Hugelius, G., Joosten, H., Barthelmes, A., Prigent, C., Aires, F., Hoyt, A. M., Davidson, N., Finlayson, C. M., Lehner, B., … McIntyre, P. B. (2023). Extensive global wetland loss over the past three centuries. *Nature*, *614*(7947), 281-286. https://www.nature.com/articles/s41586-022-05572-6

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R., Chapin, F. S., Seto, K. C., Weber, E. U., Crona, B. I., Daily, G. C., Dasgupta, P., Gaffney, O., Gordon, L. J., Hoff, H., Levin, S. A., … Walker, B. H. (2021). Our future in the Anthropocene biosphere. *Ambio*, *50*(4), 834-869. https://doi.org/10.1007/s13280-021-01544-8

Foster, J. B. (2022). *Capitalism in the Anthropocene: Ecological Ruin or Ecological Revolution*. NYU Press.

Foster, J. B., Clark, B., & York, R. (2011). *The Ecological Rift: Capitalism's War on the Earth*. NYU Press.

Frappart, F., Blarel, F., Fayad, I., Bergé-Nguyen, M., Crétaux, J.-F., Shu, S., Schregenberger, J., & Baghdadi, N. (2021). Evaluation of the Performances of Radar and Lidar Altimetry Missions for Water Level Retrievals in Mountainous Environment: The Case of the Swiss Lakes. *Remote Sensing*, *13*(11), 2196. https://doi.org/10.3390/rs13112196

Frassl, M. A., Boehrer, B., Holtermann, P. L., Hu, W., Klingbeil, K., Peng, Z., Zhu, J., & Rinke, K. (2018). Opportunities and Limits of Using Meteorological Reanalysis Data for Simulating Seasonal to Sub-Daily Water Temperature Dynamics in a Large Shallow Lake. *Water*, *10*(5), Article 5. https://doi.org/10.3390/w10050594

Freshwater Health Index. (2025). Freshwater Health Index. https://www.freshwaterhealthindex.org

Fuentes, I., Fuster, R., Avilés, D., & Vervoort, W. (2021). Water scarcity in central Chile: The effect of climate and land cover changes on hydrologic resources. *Hydrological Sciences Journal*, *66*(6), 1028-1044. https://doi.org/10.1080/02626667.2021.1903475

Fuentes-Hernández, P., Barría-Catalán, T., & Flores-Chávez, J. (2024). Estado, ferrocarril y territorio: Las estrategias gubernamentales para la ocupación de La Araucanía a fines del siglo XIX. *Revista Austral de Ciencias Sociales*, (46), Article 46. http://revistas.uach.cl/index.php/racs/article/view/7557

Fuenzalida, H. (1982). A country of extreme climate. *Chile: Essence and Evolution*, 27-35.

Fundación Terram. (2021). *MINUTA RELATIVA A LA MORTALIDAD MASIVA DE SALMONES CAUSADAS POR FLORACIONES ALGALES NOCIVAS (FAN) EN LAS REGIONES DE LOS LAGOS Y AYSÉN*. https://www.terram.cl/descargar/recursos_naturales/salmonicultura/Minuta-Mortalidad-Masiva-de-Salmones-en-Los-Lagos-y-AyseCC81n.pdf

Fustos-Toribio, I., Manque-Roa, N., Vásquez Antipan, D., Hermosilla Sotomayor, M., & Letelier Gonzalez, V. (2022). Rainfall-induced landslide early warning system based on corrected mesoscale numerical models: An application for the southern Andes. *Natural Hazards and Earth System Sciences*, *22*(6), 2169-2183. https://doi.org/10.5194/nhess-22-2169-2022

Galarce, L. C. (2020, julio 3). Protección de los ecosistemas acuáticos ante la presión de la crisis económica que viene. *CIPER Chile*. https://www.ciperchile.cl/2020/07/03/proteccion-de-los-ecosistemas-acuaticos-ante-la-presion-de-la-crisis-economica-que-viene/

Gao, H., Birkett, C., & Lettenmaier, D. P. (2012). Global monitoring of large reservoir storage from satellite remote sensing. *Water Resources Research*, *48*(9). https://doi.org/10.1029/2012WR012063

Gao, Y., Xie, Y., & Zou, D. (2020). Hydrological regime change and its ecological responses in East Dongting Lake, China. *Ecohydrology & Hydrobiology*, *20*(1), 142-150. https://doi.org/10.1016/j.ecohyd.2019.07.003

Garreaud, R. D. (2009). The Andes climate and weather. *Advances in Geosciences*, *22*, 3-11. https://doi.org/10.5194/adgeo-22-3-2009

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., & Veloso-Aguila, D. (2020). The Central Chile Mega Drought (2010–2018): A

climate dynamics perspective. *International Journal of Climatology*, *40*(1), 421-439. https://doi.org/10.1002/joc.6219

Garreaud, R. D., Vuille, M., Compagnucci, R., & Marengo, J. (2009). Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology, Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives*, *281*(3), 180-195. https://doi.org/10.1016/j.palaeo.2007.10.032

Gell, P. A., Finlayson, C. M., & Davidson, N. C. (2023). 1—An introduction to the Ramsar Convention on Wetlands. En P. A. Gell, N. C. Davidson, & C. M. Finlayson (Eds.), *Ramsar Wetlands* (pp. 1-36). Elsevier. https://doi.org/10.1016/B978-0-12-817803-4.00018-8

Gerding, V. (2010). *Suelos de humedales y trumaos húmedos del sur de Chile*. http://biblioteca.cehum.org/handle/CEHUM2018/1628

Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. *Sensors*, *16*(8), 1298. https://doi.org/10.3390/s16081298

Gozingan, A. S., Sohou, Z., Baetens, K., Bonou, F., Baloïtcha, E., Gourgue, O., Romanelli, H., Capet, A., & Lacroix, G. (2024). A 3D numerical baroclinic application of the COHERENS model in the Gulf of Guinea, West Africa. *Regional Studies in Marine Science*, *79*, 103811. https://doi.org/10.1016/j.rsma.2024.103811

Granata, F., & Di Nunno, F. (2025). Pathways for Hydrological Resilience: Strategies for Adaptation in a Changing Climate. *Earth Systems and Environment*. https://doi.org/10.1007/s41748-024-00567-x

Gubrium, J. F., Holstein, J. A., Marvasti, A. B., & McKinney, K. D. (2012). *The SAGE Handbook of Interview Research: The Complexity of the Craft*. SAGE Publications.

Gudynas, E. (2014). *Cuando los extractivismos reconPguran democracias y derechos Tensiones y contradicciones bajo el progresismo realmente gobernante*.

Gudynas, E. (2015). *Derechos de la naturaleza: Ética biocéntrica y políticas ambientales*. Editorial Abya-Yala. https://books.google.es/books?hl=es&lr=&id=FONZEAAAQBAJ&oi=fnd&pg=PA5&dq=gudynas+2015+pol%C3%ADticas+ambientales&ots=XWxfwm2CuX&sig=WCdqNCNGMdVkOrztuZc7SztKDPU

Gudynas, E. (2017). Beyond varieties of development: Disputes and alternatives. En *Rising Powers and South-South Cooperation*. Routledge.

Guo, M., Zhuang, Q., Yao, H., Golub, M., Leung, L. R., Pierson, D., & Tan, Z. (2021). Validation and Sensitivity Analysis of a 1-D Lake Model Across Global Lakes. *Journal of Geophysical Research: Atmospheres*, *126*(4), e2020JD033417. https://doi.org/10.1029/2020JD033417

Guo, Y., Ren, Z., Dong, Y., Zhang, P., Wang, C., Ma, Z., & He, X. (2023). Multifunctionality can be promoted by increasing agriculture-dominated heterogeneous landscapes in an agro-forestry interlacing zone in northeast China. *Landscape and Urban Planning*, *238*, 104832. https://doi.org/10.1016/j.landurbplan.2023.104832

Hammer, D. A., & Bastian, R. K. (1989). Wetlands Ecosystems: Natural Water Purifiers? En *Constructed Wetlands for Wastewater Treatment*. CRC Press.

Hansen, G. J. A., Wehrly, K. E., Vitense, K., Walsh, J. R., & Jacobson, P. C. (2022). Quantifying the resilience of coldwater lake habitat to climate and land use change to prioritize watershed conservation. *Ecosphere*, *13*(7), e4172. https://doi.org/10.1002/ecs2.4172

Hansen, G., & Stone, D. (2016). Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, *6*(5), 532-537. https://doi.org/10.1038/nclimate2896

Hargrove, A. (2021). The global water crises: A cross-national analysis of metabolic rift theory. *Journal of Political Ecology*, *28*, 2925. https://doi.org/10.2458/jpe.2925

Haustein, K., Allen, M. R., Forster, P. M., Otto, F. E. L., Mitchell, D. M., Matthews, H. D., & Frame, D. J. (2017). A real-time Global Warming Index. *Scientific Reports*, *7*(1), 15417. https://doi.org/10.1038/s41598-017-14828-5

He, C., Malcolm, S. B., Dahlberg, K. A., & Fu, B. (2000). A conceptual framework for integrating hydrological and biological indicators into watershed management. *Landscape and Urban Planning*, *49*(1), 25-34. https://doi.org/10.1016/S0169-2046(00)00047-5

Heilmayr, R., Echeverría, C., Fuentes, R., & Lambin, E. F. (2016). A plantation-dominated forest transition in Chile. *Applied Geography*, *75*, 71-82. https://www.sciencedirect.com/science/article/pii/S0143622816302600

Hernandez, D., Mendoza, P. A., Boisier, J. P., & Ricchetti, F. (2022). Hydrologic Sensitivities and ENSO Variability Across Hydrological Regimes in Central Chile (28°–41°S). *Water Resources Research*, *58*(9), e2021WR031860. https://doi.org/10.1029/2021WR031860

Herod, A. (1993). Gender Issues in the Use of Interviewing as a Research Method∗. *The Professional Geographer*, *45*(3), 305-317. https://doi.org/10.1111/j.0033-0124.1993.00305.x

Hersbach. (2023). *ERA5 hourly data on single levels from 1940 to present*. https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview

Hipsey, M. R., Bruce, L. C., Boon, C., Busch, B., Carey, C. C., Hamilton, D. P., Hanson, P. C., Read, J. S., de Sousa, E., Weber, M., & Winslow, L. A. (2019). A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geoscientific Model Development*, *12*(1), 473-523. https://doi.org/10.5194/gmd-12-473-2019

Hodges, B. R., Imberger, J., & Laval, B. (2000). *Modeling the Hydrodynamics of Stratified Lakes*.

Holling, C. S. (1986). The resilience of terrestrial ecosystems: Local surprise and global change. *Sustainable development of the biosphere*, *14*, 292-317.

Hosseini-Sadabadi, S. A., Rousseau, A. N., Sadeghian, A., Foulon, E., & Behmel, S. (2023). A 3D numerical modeling of the links between hydrodynamics, dissolved oxygen, and water temperature of a northern rural-urban shallow lake with two distinct basins. *Environmental Monitoring and Assessment*, *195*(10), 1198. https://doi.org/10.1007/s10661-023-11744-2

Hou, M., Wei, J., Chu, H., Shi, Y., Ayantobo, O. O., Xu, J., Zhu, X., & Ren, Y. (2022). Conceptual hydrological model-guided SVR approach for monthly lake level reconstruction in the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *44*, 101271. https://doi.org/10.1016/j.ejrh.2022.101271

Hu, S., Niu, Z., & Chen, Y. (2017). Global Wetland Datasets: A Review. *Wetlands*, *37*(5), 807-817. https://doi.org/10.1007/s13157-017-0927-z

Hu, S., Niu, Z., Chen, Y., Li, L., & Zhang, H. (2017). Global wetlands: Potential distribution, wetland loss, and status. *Science of The Total Environment*, *586*, 319-327. https://www.sciencedirect.com/science/article/pii/S0048969717302425

Huang, J., Yu, H., Han, D., Zhang, G., Wei, Y., Huang, J., An, L., Liu, X., & Ren, Y. (2020). Declines in global ecological security under climate change. *Ecological Indicators*, *117*, 106651. https://www.sciencedirect.com/science/article/pii/S1470160X20305884

Huang, L., Wang, J., & Chen, X. (2022). Ecological infrastructure planning of large river basin to promote nature conservation and ecosystem functions. *Journal of Environmental Management*, *306*, 114482. https://www.sciencedirect.com/science/article/pii/S030147972200055X

Huang, L., Woolway, R. I., Timmermann, A., Lee, S.-S., Rodgers, K. B., & Yamaguchi, R. (2024). Emergence of lake conditions that exceed natural temperature variability. *Nature Geoscience*, *17*(8), 763-769. https://doi.org/10.1038/s41561-024-01491-5

Huenupil-Marihuen., M., Garces-Vargas, M., Llevilao-Colil, O., L., A.-P., & Medina-Riquelme, F. (2010). *Historia de Tirúa*.

Huttula, T., & Liukko, N. (2014). *Lake Pyykösjärvi water quality model*.

IDE. (2025). *Infraestructura de datos espaciales. Geoportal de Chile*. https://www.geoportal.cl/catalog

IDE minagri. (2025). *Planificación Catastral | IDE minagri*. https://ide.minagri.gob.cl/geoweb/2019/11/22/planificacion-catastral/

Imberger, J., & Patterson, J. C. (1989). Physical Limnology. En J. W. Hutchinson & T. Y. Wu (Eds.), *Advances in Applied Mechanics* (Vol. 27, pp. 303-475). Elsevier. https://doi.org/10.1016/S0065-2156(08)70199-6

INEa. (2017). *ArcGIS Web Application*. https://ine-chile.maps.arcgis.com/apps/webappviewer/index.html?id=d0bff7af90384faa98d6ff69faa0d6d2

INEb. (2024). *Censo de Población y Vivienda*. Default. http://www.ine.gob.cl/estadisticas/sociales/censos-de-poblacion-y-vivienda/censo-de-poblacion-y-vivienda

INFOR, I. (2014). *Exportaciones forestales chilenas 2013*. INFOR. https://doi.org/10.52904/20.500.12220/20791

Interferencia. (2023, febrero 14). *Ministro de Economía confirma postergación de debate sobre nueva regulación forestal planteada por Boric*. Interferencia. https://interferencia.cl/articulos/ministro-de-economia-confirma-postergacion-de-debate-sobre-nueva-regulacion-forestal

International Lake Environment Committee, I. L. E. C. (2007). Integrated lake basin management: An introduction. *International Lake Environment Committee Foundation. Kusatsu, Japan*, *26*.

International Lake EnvironmentCommitte, I. L. E. (2005). *Managing lakes and their basins for sustainable use: A report for lake basin managers and stakeholders*. International Lake Environment Committee Foundation. https://cir.nii.ac.jp/crid/1971430859734593319

Ishikawa, M., Gonzalez, W., Golyjeswski, O., Sales, G., Rigotti, J. A., Bleninger, T., Mannich, M., & Lorke, A. (2022). Effects of dimensionality on the performance

of hydrodynamic models for stratified lakes and reservoirs. *Geoscientific Model Development*, *15*(5), 2197-2220. https://doi.org/10.5194/gmd-15-2197-2022

Iturra Urzúa, J. M. (2024). *Saqueo al humedal de Quilicura. Construcciones sobre el agua*. https://repositorio.uchile.cl/handle/2250/198083

Jacques Coper, M., & Garreaud Salazar, R. (2015). *Characterization of the 1970s climate shift in South America*. https://doi.org/10.1002/joc.4120

Jansen, J., Simpson, G. L., Weyhenmeyer, G. A., Härkönen, L. H., Paterson, A. M., del Giorgio, P. A., & Prairie, Y. T. (2024). Climate-driven deoxygenation of northern lakes. *Nature Climate Change*, *14*(8), 832-838. https://doi.org/10.1038/s41558-024-02058-3

Jerlov. (1968). *Optical Oceanography*. Elsevier.

Ji, L., Senay, G. B., & Verdin, J. P. (2015). *Evaluation of the Global Land Data Assimilation System (GLDAS) Air Temperature Data Products*. https://doi.org/10.1175/JHM-D-14-0230.1

Jian, J., Ryu, D., Costelloe, J. F., & Su, C.-H. (2017). Towards hydrological model calibration using river level measurements. *Journal of Hydrology: Regional Studies*, *10*, 95-109. https://doi.org/10.1016/j.ejrh.2016.12.085

Jiang, Q., Li, W., Fan, Z., He, X., Sun, W., Chen, S., Wen, J., Gao, J., & Wang, J. (2021). Evaluation of the ERA5 reanalysis precipitation dataset over Chinese Mainland. *Journal of Hydrology*, *595*, 125660. https://doi.org/10.1016/j.jhydrol.2020.125660

Jorgensen, S. E., & Rast, W. (2007). The use of models for synthesizing knowledge for integrated lake basin management, and facilitating implementation of the World Lake Vision. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *12*(1), 3-13. https://doi.org/10.1111/j.1440-1770.2007.00316.x

Kanazawa, M. (2023). *Research Methods for Environmental Studies: A Social Science Approach* (2.ª ed.). Routledge. https://doi.org/10.4324/9781003261117

Kay, J. J., & Schneider, E. (1995). Embracing Complexity the Challenge of the Ecosystem Approach. En L. Westra & J. Lemons (Eds.), *Perspectives on Ecological Integrity* (pp. 49-59). Springer Netherlands. https://doi.org/10.1007/978-94-011-0451-7_4

Kaya, Y. (2025). Evaluation of ICESat-2 Laser Altimetry for Inland Water Level Monitoring: A Case Study of Canadian Lakes. *Water*, *17*(7), 1098. https://doi.org/10.3390/w17071098

Kaya, Y., Balik Sanli, F., & Abdikan, S. (2025). Refinement of ICESat-2 derived inland water surface levels with the TG20 local geoid model: In the case of Türkiye lakes. *Physics and Chemistry of the Earth, Parts A/B/C*, *139*, 103900. https://doi.org/10.1016/j.pce.2025.103900

King, A. W. (1993). Considerations of Scale and Hierarchy. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Kirby, R. R., Beaugrand, G., Kleparski, L., Goodall, S., & Lavender, S. (2021). Citizens and scientists collect comparable oceanographic data: Measurements of ocean transparency from the Secchi Disk study and science programmes. *Scientific Reports*, *11*(1), 15499. https://doi.org/10.1038/s41598-021-95029-z

KNMI. (2024). *KNMI Climate explorer*. https://climexp.knmi.nl/selectindex.cgi?id=someone@somewhere

Kondo, J. (1975). Air-sea bulk transfer coefficients in diabatic conditions. *Boundary-Layer Meteorology*, *9*(1), 91-112. https://doi.org/10.1007/BF00232256

Korkou, M., Tarigan, A. K. M., & Hanslin, H. M. (2023). The multifunctionality concept in urban green infrastructure planning: A systematic literature review. *Urban Forestry & Urban Greening*, *85*, 127975. https://doi.org/10.1016/j.ufug.2023.127975

Kornijów, R. (2023). Lake aging concept revisited: Alternative comprehensive approach to lake ontogeny. *Canadian Journal of Fisheries and Aquatic Sciences*, *80*(8), 1385-1393. https://doi.org/10.1139/cjfas-2023-0027

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259-263. https://doi.org/10.1127/0941-2948/2006/0130

Kreakie, B. J., Shivers, S. D., Hollister, J. W., & Milstead, W. B. (2021). Predictive Model of Lake Photic Zone Temperature Across the Conterminous United States. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.707874

Kumar, L., & Mutanga, O. (2018). Google Earth Engine Applications Since Inception: Usage, Trends, and Potential. *Remote Sensing*, *10*(10), Article 10. https://doi.org/10.3390/rs10101509

Kwak, T. J., & Freeman, M. (2010). *Assessment and management of ecological integrity: Chapter 12*. 353-394. https://pubs.usgs.gov/publication/70154946

Labraña-Muñoz, C., & Arcas-Morales, G. (2006). San Pedro de la Paz: Del Fuerte a la comuna (1604-2001). *Hualpén, Chile: Impresos Andalién, Ilustre Municipalidad de San Pedro de la Paz*.

Lara, A., Jones, J., Little, C., & Vergara, N. (2021). Streamflow response to native forest restoration in former Eucalyptus plantations in south central Chile. *Hydrological Processes*, *35*(8), e14270. https://doi.org/10.1002/hyp.14270

Lara, A., Solari, M. E., Prieto, M. D. R., & Peña, M. P. (2012). Reconstrucción de la cobertura de la vegetación y uso del suelo hacia 1550 y sus cambios a 2007 en la ecorregión de los bosques valdivianos lluviosos de Chile (35º—43º 30´ S). *Bosque (Valdivia)*, *33*(1), 13-23. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-92002012000100002&lng=es&nrm=iso&tlng=en

Lee, J.-W., Park, S.-R., & Lee, S.-W. (2023). Effect of Land Use on Stream Water Quality and Biological Conditions in Multi-Scale Watersheds. *Water*, *15*(24), 4210. https://doi.org/10.3390/w15244210

Lee, K., Nam, S., Cho, Y.-K., Jeong, K.-Y., & Byun, D.-S. (2022). Determination of Long-Term (1993–2019) Sea Level Rise Trends Around the Korean Peninsula Using Ocean Tide-Corrected, Multi-Mission Satellite Altimetry Data. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.810549

Lewis, S. L., & Maslin, M. A. (2015). Defining the Anthropocene. *Nature*, *519*(7542), 171-180. https://www.nature.com/articles/nature14258

Lieberherr, G., & Wunderle, S. (2018). Lake Surface Water Temperature Derived from 35 Years of AVHRR Sensor Data for European Lakes. *Remote Sensing*, *10*(7), Article 7. https://doi.org/10.3390/rs10070990

Lin, S., Boegman, L., Shan, S., & Mulligan, R. (2022). An automatic lake-model application using near-real-time data forcing: Development of an operational forecast workflow (COASTLINES) for Lake Erie. *Geoscientific Model Development*, *15*(3), 1331-1353. https://doi.org/10.5194/gmd-15-1331-2022

Little, C., Lara, A., McPhee, J., & Urrutia, R. (2009). Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile. *Journal of Hydrology*, *374*(1), 162-170. https://doi.org/10.1016/j.jhydrol.2009.06.011

Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., Valenzuela, R. A., Llorca-Jaña, M., Ortiz, C. R., Navarrete-Montalvo, J., & Valenzuela, R. A. (2017). La agricultura y la élite agraria chilena a través de los catastros agrícolas, c. 1830-1855. *Historia (Santiago)*, *50*(2), 597-639. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0717-71942017000200597&lng=es&nrm=iso&tlng=es

Long, L. (2017, marzo 1). The Stages of Lake and Pond Succession. *SOLitude Lake Management: Full-Service Lake And Pond Management*. https://www.solitudelakemanagement.com/the-stages-of-lake-and-pond-succession/

Lovell, S. T. (2010). Multifunctional Urban Agriculture for Sustainable Land Use Planning in the United States. *Sustainability*, *2*(8), 2499-2522. https://doi.org/10.3390/su2082499

Luo, J., Duan, H., Xu, Y., Shen, M., Zhang, Y., Xiao, Q., Ni, G., Wang, K., Xin, Y., Qi, T., Feng, L., Qiu, Y., Jeppesen, E., & Woolway, R. I. (2025). Global trends and regime state shifts of lacustrine aquatic vegetation. *The Innovation*, *6*(3), 100784. https://doi.org/10.1016/j.xinn.2024.100784

Luyten, P. (2025). *COHERENS: A Coupled Hydrodynamical Ecological Model for Regional and Shelf Seas: User Documentation (Version 3)*. Operational Directorate Natural Environment, Royal Belgian Institute of Natural Sciences. https://doi.org/10.5281/zenodo.11261106.

Lyche Solheim, A., Globevnik, L., Austnes, K., Kristensen, P., Moe, S. J., Persson, J., Phillips, G., Poikane, S., van de Bund, W., & Birk, S. (2019). A new broad typology for rivers and lakes in Europe: Development and application for large-scale environmental assessments. *Science of The Total Environment*, *697*, 134043. https://doi.org/10.1016/j.scitotenv.2019.134043

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J. B., Jena, J., Bhattacharya, U., Duvvada, S. K., Lalichetti, S., & Sairam, M. (2021). Intercropping—A Low Input Agricultural Strategy for Food and Environmental Security. *Agronomy*, *11*(2), Article 2. https://www.mdpi.com/2073-4395/11/2/343

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015a). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*, 331-340. https://doi.org/10.1016/j.agwat.2015.06.022

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015b). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agricultural Water Management*, *159*(C), 331-340. https://ideas.repec.org//a/eee/agiwat/v159y2015icp331-340.html

Mano, A., Malve, O., Koponen, S., Kallio, K., Taskinen, A., Ropponen, J., Juntunen, J., & Liukko, N. (2015). Assimilation of satellite data to 3D hydrodynamic model of Lake Säkylän Pyhäjärvi. *Water Science and Technology*, *71*(7), 1033-1039. https://doi.org/10.2166/wst.2015.042

Mano, A., & Shuku, T. (2014). *Application of the Particle Filter to COHERENS V2 model of Lake Säkylän Pyhäjärvi*.

Manuschevich, D. (2016). Neoliberalization of forestry discourses in Chile. *Forest Policy and Economics*, *69*, 21-30. https://doi.org/10.1016/j.forpol.2016.03.006

Marinov, D., Norro, A., & Zaldívar, J.-M. (2006). Application of COHERENS model for hydrodynamic investigation of Sacca di Goro coastal lagoon (Italian Adriatic Sea shore). *Ecological Modelling, Special Issue on Southern European Coastal Lagoons*, *193*(1), 52-68. https://doi.org/10.1016/j.ecolmodel.2005.07.042

Martínez Retureta, R. (2021). *Efectos del cambio de uso cobertura del suelo sobre la respuesta hidrológica en cuencas del centro sur de Chile bajo escenarios de cambio climático.* https://repositorio.udec.cl/handle/11594/6538

Martínez-Fernández, J., Banos-González, I., & Esteve-Selma, M. Á. (2021). An integral approach to address socio-ecological systems sustainability and their uncertainties. *Science of The Total Environment*, *762*, 144457. https://www.sciencedirect.com/science/article/pii/S0048969720379882

Martínez-Tilleria, K., Núñez-Ávila, M., León, C. A., Pliscoff, P., Squeo, F. A., & Armesto, J. J. (2017). A framework for the classification Chilean terrestrial ecosystems as a tool for achieving global conservation targets. *Biodiversity and Conservation*, *26*(12), 2857-2876. https://doi.org/10.1007/s10531-017-1393-x

Marttunen, M., Hellsten, S., Glover, B., Tarvainen, A., Klintwall, L., Olsson, H., & Pedersen, T. S. (2006). Heavily regulated lakes and the European Water framework directive—Comparisons from Finland, Norway, Sweden, Scotland and Austria. *E-Water*, *5*, 1-22. https://www.ewa-online.eu/files/downloads/publications/E-Water_Journal/42_2006_05.pdf

Mason, I. M., Guzkowska, M. A. J., Rapley, C. G., & Street-Perrott, F. A. (1994). The response of lake levels and areas to climatic change. *Climatic Change*, *27*(2), 161-197. https://doi.org/10.1007/BF01093590

Mayer, A. L., & Rietkerk, M. (2004). The Dynamic Regime Concept for Ecosystem Management and Restoration. *BioScience*, *54*(11), 1013-1020. https://doi.org/10.1641/0006-3568(2004)054[1013:TDRCFE]2.0.CO;2

McDougall, T. J., Jackett, D. R., Wright, D. G., & Feistel, R. (2003). *Accurate and Computationally Efficient Algorithms for Potential Temperature and Density of Seawater*. https://journals.ametsoc.org/view/journals/atot/20/5/1520-0426_2003_20_730_aaceaf_2_0_co_2.xml

McGregor, G. (2017). Hydroclimatology, modes of climatic variability and stream flow, lake and groundwater level variability: A progress report. *Progress in Physical Geography: Earth and Environment*, *41*(4), 496-512. https://doi.org/10.1177/0309133317726537

Meerhoff, M., Audet, J., Davidson, T. A., De Meester, L., Hilt, S., Kosten, S., Liu, Z., Mazzeo, N., Paerl, H., Scheffer, M., & Jeppesen, E. (2022). Feedback between climate change and eutrophication: Revisiting the allied attack concept and how to strike back. *Inland Waters*, *12*(2), 187-204. https://doi.org/10.1080/20442041.2022.2029317

Mellor, G. L. (1988). *A THREE-DIMENSIONAL, PRIMITIVE EQUATION, NUMERICAL OCEAN MODEL*.

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016a). Trophic State Index estimation from remote sensing of lake Chapala,

México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., Ruiz-Armenta, J. R., Membrillo-Abad, A.-S., Torres-Vera, M.-A., Alcocer, J., Prol-Ledesma, R. M., Oseguera, L. A., & Ruiz-Armenta, J. R. (2016b). Trophic State Index estimation from remote sensing of lake Chapala, México. *Revista Mexicana de Ciencias Geológicas*, *33*(2), 183-191. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S1026-87742016000200183&lng=es&nrm=iso&tlng=en

Meng, B., Liu, J., Bao, K., & Sun, B. (2020). Methodologies and Management Framework for Restoration of Wetland Hydrologic Connectivity: A Synthesis. *Integrated Environmental Assessment and Management*, *16*(4), 438-451. https://doi.org/10.1002/ieam.4256

Merryfield, W. J., & Lee, W.-S. (2023). Estimating Probabilities of Extreme ENSO Events from Copernicus Seasonal Hindcasts. *Asia-Pacific Journal of Atmospheric Sciences*, *59*(4), 479-493. https://doi.org/10.1007/s13143-023-00328-2

Metcalfe, A. N., Kennedy, T. A., Mendez, G. A., & Muehlbauer, J. D. (2022). Applied citizen science in freshwater research. *WIREs Water*, *9*(2), e1578. https://doi.org/10.1002/wat2.1578

Mironov, D., Golosov, S., Heise, E., Kourzeneva, E., Ritter, B., Schneider, N., & Terzhevik, A. (2005). FLake – A Lake Model for Environmental Applications. *2005*.

Mitra, S., Wassmann, R., & Vlek, P. L. G. (2003). *Global inventory of wetlands and their role in the carbon cycle* (ZEF - Discussion Papers on Development Policy No. 64). https://doi.org/10.22004/ag.econ.18771

MMA. (2020). *ANTEPROYECTO DEL PLAN DE DESCONTAMINACION POR CLOROFILA "A", TliANSPARENCIA Y FOSFORO DISUELTO, PARA LA CUENCA DEL LAGO VILLARRICA.* https://consultaindigena.mma.gob.cl/wp-content/uploads/2021/11/Anteproyecto-PDA-Lago-Villarrica.pdf

Montecinos, A., & Aceituno, P. (2003). *Seasonality of the ENSO-Related Rainfall Variability in Central Chile and Associated Circulation Anomalies*. https://journals.ametsoc.org/view/journals/clim/16/2/1520-0442_2003_016_0281_soterr_2.0.co_2.xml

Morales-Magaña, M., Paneque-Galvez, J., Torres-Abreu, A., Mori-González, R., Reyes Díaz, A. M., Rivera Ramos, J. C., Molina Carrasquillo, R., & Molina Parrilla, S. C. (2020). *Community experiences in water management: Social innovation, participatory science, and dialogue of knowledges II (in Portuguese and Spanish)*. https://doi.org/10.5281/zenodo.4362629

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, *50*(3), 885-900. https://doi.org/10.13031/2013.23153

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). *Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria*.

Mortimer, C. H. (1974). Lake hydrodynamics. *Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Mitteilungen*. (world). https://www.tandfonline.com/doi/abs/10.1080/05384680.1974.11923886

Mukaka, M. M. (2012). A guide to appropriate use of Correlation coefficient in medical research. *Malawi Medical Journal*, *24*(3), 69-71. https://www.ajol.info/index.php/mmj/article/view/81576

Muñoz Aguayo, P. (2013). *Apuntes de teledetección: Índices de vegetación.* https://bibliotecadigital.ciren.cl/bitstreams/af8fd625-0d58-4941-8530-7186a6b3d93e/download

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349-4383. https://doi.org/10.5194/essd-13-4349-2021

Naciones Unidas, M. J. (2025). Objetivos y metas de desarrollo sostenible. *Desarrollo Sostenible*. https://www.un.org/sustainabledevelopment/es/objetivos-de-desarrollo-sostenible/

NASA. (2025). *ASF Data Search*. https://search.asf.alaska.edu/

NASA SWOT. (2024). *NASA SWOT. Jet Propulsion Laboratory: Surface Water and Ocean Topography (SWOT).* https://swot.jpl.nasa.gov/

National Institute of Water and Atmospheric Research. (2025). *Lakespi (Lake Submerged Plant Indicators)*. https://lakespi.niwa.co.nz/

Ndehedehe, C. E., Awange, J. L., Kuhn, M., Agutu, N. O., & Fukuda, Y. (2017). Analysis of hydrological variability over the Volta river basin using in-situ data and satellite observations. *Journal of Hydrology: Regional Studies*, *12*, 88-110. https://doi.org/10.1016/j.ejrh.2017.04.005

Nekouee, N., Hamidi, S. A., Roberts, P. J. W., & Schwab, D. J. (2015). Assessment of a 3D Hydrostatic Model (POM) in the Near Field of a Buoyant River Plume in Lake Michigan. *Water, Air, & Soil Pollution*, *226*(7), 210. https://doi.org/10.1007/s11270-015-2488-1

Ngamile, S., Madonsela, S., & Kganyago, M. (2025). Trends in remote sensing of water quality parameters in inland water bodies: A systematic review. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1549301

Nhamo, L., Magidi, J., & Dickens, C. (2017). Determining wetland spatial extent and seasonal variations of the inundated area using multispectral remote sensing. *Water SA*, *43*(4), 543-552. https://doi.org/10.4314/wsa.v43i4.02

Nielsen, L. (2020, enero). *(PDF) Toward a unified theory of risk, resilience and sustainability science with applications for education and governance*. https://www.researchgate.net/publication/348407042_Toward_a_unified_theory_of_risk_resilience_and_sustainability_science_with_applications_for_education_and_governance

NOAA. (2024a). *El Niño / Southern Oscillation (ENSO) | Equatorial Pacific Sea Surface Temperatures (SST) | National Centers for Environmental Information (NCEI)*. https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024b). *National Oceanic and Atmospheric Administration (NOAA). Antartic Oscillation.* https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml

NOAA. (2024c). *National Oceanic and Atmospheric Administration (NOAA). Equatorial Pacific Sea Surface Temperatures (SST).* https://www.ncei.noaa.gov/access/monitoring/enso/sst

NOAA. (2024d). *National Oceanic and Atmospheric Administration (NOAA). Pacific Decadal Oscillation (PDO).* https://www.ncei.noaa.gov/access/monitoring/pdo/

Odeku, K. O. (2022). Climate injustices due to the unequal and disproportionate impacts of climate change. *Perspectives of Law and Public Administration*, *11*(1), 103-110. https://www.ceeol.com/search/article-detail?id=1102605

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., & Calvez, R. (2018). Surface water monitoring in small water bodies: Potential and limits of multi-sensor Landsat time series. *Hydrology and Earth System Sciences*, *22*(8), 4349-4380. https://doi.org/10.5194/hess-22-4349-2018

Olvera, M. J. T. (2018). *Integridad ecológica como una herramienta de evaluación en cuencas hidrográficas. Caso de estudio Microcuenca del Río Jalpan*. https://ri-ng.uaq.mx/handle/123456789/1004

Onyutha, C. (2021). A hydrological model skill score and revised R-squared. *Hydrology Research*, *53*(1), 51-64. https://doi.org/10.2166/nh.2021.071

Oppliger, A. (2015). *Atlas del Agua – Chile 2016 / Atlas of Water—Chile 2016*. Ministry of Public Works - General Direction of Waters of Chile. https://iris.unil.ch/handle/iris/49995

O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J. D., McIntyre, P. B., Kraemer, B. M., Weyhenmeyer, G. A., Straile, D., Dong, B., Adrian, R., Allan, M. G., Anneville, O., Arvola, L., Austin, J., Bailey, J. L., … Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, *42*(24), 10,773-10,781. https://doi.org/10.1002/2015GL066235

Organización del Tratado de Cooperación Amazónica. (2025). *Proyecto Cuenca Amazónica. Implementación del Programa de Acciones Estratégicas en la Cuenca del río Amazonas considerando la Variabilidad y el Cambio Climático.* https://aguasamazonicas.otca.org/monitoreo-ambiental-y-de-los-recursos-hidricos/sistema-integrado-de-monitoreo-de-los-recursos-hidricos/

Ortiz, A. M. D., Gayó, E. M., Henríquez, N. C., Henríquez, B. J., & Pauchard, A. (2024). Exploring the multifunctional landscapes model in areas dominated by non-native tree plantations. *Trees, Forests and People*, *17*, 100617. https://www.sciencedirect.com/science/article/pii/S2666719324001249

Otavo, S., & Echeverría, C. (2017). Fragmentación progresiva y pérdida de hábitat de bosques naturales en uno de los hotspot mundiales de biodiversidad. *Revista Mexicana de Biodiversidad*, *88*(4), 924-935. https://doi.org/10.1016/j.rmb.2017.10.041

Otero Durán, L. (2012). La huella del fuego: Historia de los bosques nativos poblamiento y cambios en el paisaje de lsur de Chile. *2012*. https://www.sidalc.net/search/Record/KOHA-OAI-FCF:15776/Description

Oxley, R. L. (2015). *Ecological, environmental and hydrological integrity in sustainable water resource management for river basins*. Arizona State University. https://search.proquest.com/openview/4d57cce5b508c9900cd2f564fdc817bd/1?pq-origsite=gscholar&cbl=18750

Palomo, I., Locatelli, B., Otero, I., Colloff, M., Crouzat, E., Cuni-Sanchez, A., Gómez-Baggethun, E., González-García, A., Grêt-Regamey, A., Jiménez-Aceituno, A., Martín-López, B., Pascual, U., Zafra-Calvo, N., Bruley, E., Fischborn, M., Metz, R., & Lavorel, S. (2021). Assessing nature-based solutions for

transformative change. *One Earth*, *4*(5), 730-741. https://doi.org/10.1016/j.oneear.2021.04.013

Paredes, M. L., & Ulloa, M. E. (2021). Implementación de los ECMPO y las disputas por el control del territorio: El caso del ECMPO Mañihueico-Huinay y los mitilicultores de la comuna de Hualaihué, Región de Los Lagos. *Revista LIDER*, 62-87. https://revistas.ulagos.cl/index.php/index

Pareeth, S., Salmaso, N., Adrian, R., & Neteler, M. (2016). Homogenised daily lake surface water temperature data generated from multiple satellite sensors: A long-term case study of a large sub-Alpine lake. *Scientific Reports*, *6*(1), 31251. https://doi.org/10.1038/srep31251

Parra et al. (2016). *Una aproximación interdisciplinaria al estudio... - Google Académico*. https://scholar.google.com/scholar_lookup?title=Una+aproximaci%C3%B3n+interdisciplinaria+al+estudio+de+floraciones+de+algas+nocivas+en+Lagos+Urbanos+En+Chile&author=Parra,+O.&author=Baeza,+C.&author=Almanza,+V.&author=Urrutia,+R.&author=Figueroa,+R.&author=Fern%C3%A1ndez,+X.&author=de+Or%C3%BAe,+P.&author=Gonz%C3%A1lez,+P.&author=Beltr%C3%A1n,+J.&author=Becerra,+J.&publication_year=2016&pages=133%E2%80%93146

Parra et al., O. (2003). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*, 51-83. https://ui.adsabs.harvard.edu/abs/2003Limne..22...51P

Parra, O. (2003a). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://doi.org/10.23818/limn.22.04

Parra, O. (2003b). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, *22*(1), 51-83. https://www.limnetica.net/documentos/limnetica/limnetica-22-1-p-51.pdf

Parra, O., Basualto, S., Urrutia, R., & Valdovinos, C. (1999). Estudio comparativo de la diversidad fitoplanctónica de cinco lagos de diferentes niveles de eutroficación del área litoral de la región del Biobio (Chile). *Gayana Botánica (Chile)*, *56*, 93-108.

Parra, O. O. (1989). *La eutroficación de la Laguna Grande de San Pedro, Concepción, Chile: Un caso de estudio.*

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005a). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Parra, O., Valdovinos, C., Basualto, S., & Urrutia, R. (2005b). Diversidad fitoplanctónica de los lagos nahuelbutanos (Chile Central). *Historia, biodiversidad y ecología de los bosques costeros de Chile*, 146-157.

Pedreros-Guarda, M. (2025). *Github COHERENS Lake*. https://github.com/mpedreros/COHERENS_Lake.git

Pedreros-Guarda, M. (2025). *Mpedreros/TesisDoctoral* [Software]. https://github.com/mpedreros/TesisDoctoral (Obra original publicada en 2025)

Pedreros-Guarda, M., Abarca-del-Río, R., Crétaux, J. F., & Paris, A. (2025). Long-term lake water levels in central Chile using satellite altimetry and conceptual hydrological modelling approaches. *Advances in Space Research*, *76*(4), 1997-2018. https://doi.org/10.1016/j.asr.2025.05.091

Pedreros-Guarda, M., Abarca-del-Río, R., Escalona, K., García, I., & Parra, Ó. (2021). A Google Earth Engine Application to Retrieve Long-Term Surface Temperature for Small Lakes. Case: San Pedro Lagoons, Chile. *Remote Sensing*, *13*(22), 4544. https://doi.org/10.3390/rs13224544

Piccioni, F., Casenave, C., Lemaire, B. J., Le Moigne, P., Dubois, P., & Vinçon-Leite, B. (2021). The thermal response of small and shallow lakes to climate change: New insights from 3D hindcast modelling. *Earth System Dynamics*, *12*(2), 439-456. https://doi.org/10.5194/esd-12-439-2021

Piccolroaz, S., Toffolon, M., & Majone, B. (2013). A simple lumped model to convert air temperature into surface water temperature in lakes. *Hydrology and Earth System Sciences*, *17*(8), 3323-3338. https://doi.org/10.5194/hess-17-3323-2013

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024a). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Piccolroaz, S., Zhu, S., Ladwig, R., Carrea, L., Oliver, S., Piotrowski, A. P., Ptak, M., Shinohara, R., Sojka, M., Woolway, R. I., & Zhu, D. Z. (2024b). Lake Water Temperature Modeling in an Era of Climate Change: Data Sources, Models, and Future Prospects. *Reviews of Geophysics*, *62*(1), e2023RG000816. https://doi.org/10.1029/2023RG000816

Pilla, R. M., Williamson, C. E., Zhang, J., Smyth, R. L., Lenters, J. D., Brentrup, J. A., Knoll, L. B., & Fisher, T. J. (2018). Browning-Related Decreases in Water Transparency Lead to Long-Term Increases in Surface Water Temperature and Thermal Stratification in Two Small Lakes. *Journal of Geophysical Research: Biogeosciences*, *123*(5), 1651-1665. https://doi.org/10.1029/2017JG004321

Pinto, A. P., García, P. B., Almonacid, L. E., & Henríquez, B. J. (2023). Zonas de Sacrificio y Recuperación Socioambiental en Chile: Fallas y oportunidades de la política ambiental. *Ambiente & Sociedade*, *26*, e01371. https://www.scielo.br/j/asoc/a/JdDjvNrLpBJPKwYfppfDBWB/

Prats, J., Reynaud, N., Rebière, D., Peroux, T., Tormos, T., & Danis, P.-A. (2018). LakeSST: Lake Skin Surface Temperature in French inland water bodies for 1999–2016 from Landsat archives. *Earth System Science Data*, *10*(2), 727-743. https://doi.org/10.5194/essd-10-727-2018

Qiao, B., Du, T., Ju, J., & Zhu, L. (2025). Water depth inversion based on ICESat-2 and Sentinel-2—A case study of Qiagui Co and Ayakekumu Lake on the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *59*, 102354. https://doi.org/10.1016/j.ejrh.2025.102354

Quevedo, F., Rojas Hernández, J., & Barra, R. O. (2022). Towards a Chilean Water Governance: A Study on the Los Batros and Paicaví Wetland Reservoirs. *Water*, *14*(18), Article 18. https://www.mdpi.com/2073-4441/14/18/2861

Quintana, J. M., & Aceituno, P. (2012). Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30-43º S. *Atmósfera*, *25*(1), 1-22. http://www.scielo.org.mx/scielo.php?script=sci_abstract&pid=S0187-62362012000100001&lng=es&nrm=iso&tlng=en

Randrianiaina, Rakotonirina, Ratiarimanana, & Lahatra. (2018). *Temperature Retrieval of Lake Itasy Using Remote Sensing*.

https://scholar.google.com/scholar_lookup?title=Temperature+Retrieval+of+Lake+Itasy+Using+Remote+Sensing&author=Randrianiaina,+J.&author=Rakotonirina,+I.&author=Ratiarimanana,+R.&author=Lahatra,+F.&publication_year=2018&journal=Resour.+Environ.&volume=8&pages=241%E2%80%93244

Regier, H. A. (1993a). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Regier, H. A. (1993b). The Notion of Natural and Cultural Integrity. En *Ecological Integrity and the Management of Ecosystems*. CRC Press.

Renting, H., Rossing, W. A. H., Groot, J. C. J., Van der Ploeg, J. D., Laurent, C., Perraud, D., Stobbelaar, D. J., & Van Ittersum, M. K. (2009). Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. *Journal of Environmental Management, Multifunctional agriculture - From farm diagnosis to farm design and institutional innovation*, *90*, S112-S123. https://doi.org/10.1016/j.jenvman.2008.11.014

Restrepo, L. A. V., & Sal, A. G. (2008). Un marco conceptual y analítico para estimar la integridad ecológica a escala de paisaje. *Arbor*, *184*(729), Article 729. https://arbor.revistas.csic.es/index.php/arbor/article/view/159

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Roche, P. K., & Campagne, C. S. (2017). From ecosystem integrity to ecosystem condition: A continuity of concepts supporting different aspects of ecosystem sustainability. *Current Opinion in Environmental Sustainability*, *29*, 63-68. https://www.sciencedirect.com/science/article/pii/S1877343517302828

Rockström, J., Donges, J. F., Fetzer, I., Martin, M. A., Wang-Erlandsson, L., & Richardson, K. (2024). Planetary Boundaries guide humanity's future on Earth. *Nature Reviews Earth & Environment*, *5*(11), 773-788. https://www.nature.com/articles/s43017-024-00597-z

Rojas Quezada, C. A., Muñiz Olivera, I., & García-López, M. Á. (2009). Estructura urbana y policentrismo en el Área Metropolitana de Concepción. *EURE (Santiago)*, *35*(105), 47-70. http://www.scielo.cl/scielo.php?script=sci_abstract&pid=S0250-71612009000200003&lng=es&nrm=iso&tlng=es

Rutllant, J., & Fuenzalida, H. (1991). Synoptic aspects of the central chile rainfall variability associated with the southern oscillation. *International Journal of Climatology*, *11*(1), 63-76. https://doi.org/10.1002/joc.3370110105

Salazar, Á., Thatcher, M., Goubanova, K., Bernal, P., Gutiérrez, J., & Squeo, F. (2024). CMIP6 precipitation and temperature projections for Chile. *Climate Dynamics*, *62*(3), 2475-2498. https://doi.org/10.1007/s00382-023-07034-9

Saloranta, T. M., & Andersen, T. (2007). MyLake—A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations. *Ecological Modelling, Uncertainty in Ecological Models*, *207*(1), 45-60. https://doi.org/10.1016/j.ecolmodel.2007.03.018

San Llorente Capdevila, A., Kokimova, A., Sinha Ray, S., Avellán, T., Kim, J., & Kirschke, S. (2020). Success factors for citizen science projects in water quality monitoring. *Science of The Total Environment*, *728*, 137843. https://doi.org/10.1016/j.scitotenv.2020.137843

Saraceni, M., Brunone, B., Silvestri, L., Meniconi, S., & Cerlini, P. B. (2025). *A Water Mass Balance–Based Procedure Using ERA5 Land Reanalysis and Level Observation to Reconstruct the Past Level Changes of Closed Lakes toward Future Management*. https://doi.org/10.1175/JHM-D-24-0019.1

Sarkar, D., Kar, S. K., Chattopadhyay, A., Shikha, Rakshit, A., Tripathi, V. K., Dubey, P. K., & Abhilash, P. C. (2020). Low input sustainable agriculture: A viable climate-smart option for boosting food production in a warming world. *Ecological Indicators*, *115*, 106412. https://www.sciencedirect.com/science/article/pii/S1470160X20303496

Sarkar, S., & Maity, R. (2021). Global climate shift in 1970s causes a significant worldwide increase in precipitation extremes. *Scientific Reports*, *11*(1), 11574. https://doi.org/10.1038/s41598-021-90854-8

Sarricolea, P., Herrera-Ossandon, M., & Meseguer-Ruiz, Ó. (2017). Climatic regionalisation of continental Chile. *Journal of Maps*, *13*(2), 66-73. https://doi.org/10.1080/17445647.2016.1259592

Sazib, N., Mladenova, I., & Bolten, J. (2018). Leveraging the Google Earth Engine for Drought Assessment Using Global Soil Moisture Data. *Remote Sensing*, *10*(8), Article 8. https://doi.org/10.3390/rs10081265

Schallenberg, M., de Winton, M. D., & Kelly, D. J. (2018). Indicators of Ecological Integrity. En D. P. Hamilton, K. J. Collier, J. M. Quinn, & C. Howard-Williams (Eds.), *Lake Restoration Handbook: A New Zealand Perspective* (pp. 367-393). Springer International Publishing. https://doi.org/10.1007/978-3-319-93043-5_11

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591-596. https://doi.org/10.1038/35098000

Schmid, M., & Read, J. (2022). Heat budget of lakes. En *Encyclopedia of inland waters* (Vol. 1, pp. 467-473). https://doi.org/10.1016/b978-0-12-819166-8.00011-6

Schmithuesen, F. (2007). Multifunctional forestry practices as a land use strategy to meet increasing private and public demands in modern societies. *Journal of Forest Science - UZPI (Czech Republic)*, *53*(6). https://agris.fao.org/search/en/providers/122644/records/647247a2e17b74d2224f615d

Schott, F. A., Wang, W., & Stammer, D. (2007). Variability of Pacific subtropical cells in the 50-year ECCO assimilation. *Geophysical Research Letters*, *34*(5). https://doi.org/10.1029/2006GL028478

Schwatke, C., Dettmering, D., Bosch, W., & Seitz, F. (2015). DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrology and Earth System Sciences*, *19*(10), 4345-4364. https://doi.org/10.5194/hess-19-4345-2015

Seidl, R., & Barthel, R. (2017). Linking scientific disciplines: Hydrology and social sciences. *Journal of Hydrology*, *550*, 441-452. https://doi.org/10.1016/j.jhydrol.2017.05.008

Shao, G. P., & Bishop, I. J. (2025). Citizen science in river monitoring: A systematic literature review of the whys and hows. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1609084

Shchepetkin, A. F., & McWilliams, J. C. (2003). A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. *Journal of Geophysical Research: Oceans*, *108*(C3). https://doi.org/10.1029/2001JC001047

Shine, K. P. (1984). Parametrization of the shortwave flux over high albedo surfaces as a function of cloud thickness and surface albedo. *Quarterly Journal of the Royal Meteorological Society*, *110*(465), 747-764. https://doi.org/10.1002/qj.49711046511

Simon, D. F., Munoz, G., Dinh, Q. T., Duy, S. V., Kavanagh, K., Smith, R., Husk, B., & Sauvé, S. (2023). Adopt a Lake: Successfully Tracking Harmful Cyanobacterial Blooms in Canadian Surface Waters Through Citizen Science. *Citizen Science: Theory and Practice*, *8*(1). https://doi.org/10.5334/cstp.655

Smagorinsky, J. (1963). *GENERAL CIRCULATION EXPERIMENTS WITH THE PRIMITIVE EQUATIONS*. https://journals.ametsoc.org/view/journals/mwre/91/3/1520-0493_1963_091_0099_gcewtp_2_3_co_2.xml

Smith, L. T. (2016). *A descolonizar las metodologías. Investigación y pueblos indígenas: A descolonizar las metodologías. Investigación y pueblos indígenas*. LOM Ediciones.

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, *10*(2), 126-139. https://doi.org/10.1065/espr2002.12.142

Sobarzo, M. B., Figueroa, D., & Arcos, D. R. (1997). The Influence of Winds and Tides in the Formation of Circulation Layers in a Bay, a Case Study: Concepción Bay, Chile. *Estuarine, Coastal and Shelf Science*, *45*(6), 729-736. https://doi.org/10.1006/ecss.1997.0233

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. *Anthropocene Review*, *2*(1), 81-98. http://www.scopus.com/inward/record.url?scp=84996501052&partnerID=8YFLogxK

Stepanenko, V. M., Goyette, S., Martynov, A., Perroud, M., Fang, X., & Mironov, D. (2010). First steps of a lake model intercomparison project: LakeMIP. *Boreal environment research*, *15*(2), 191. https://search.proquest.com/openview/d60a3674e3599840e062b6afc6aff527/1?pq-origsite=gscholar&cbl=5500736

Suazo, B. (2014). Fragmentación socioespacial en el barrio Boca Sur, San Pedro de la Paz: La necesidad de implementar una planificación participativa. *Universidad de Concepción*.

Sullivan, C. J., Read, J. S., & Hansen, G. J. A. (2025). Climate-driven alterations of lake thermal regimes. *Limnology and Oceanography*, *70*(8), 2348-2364. https://doi.org/10.1002/lno.70128

Sultana, F. (2022). Critical climate justice. *The Geographical Journal*, *188*(1), 118-124. https://onlinelibrary.wiley.com/doi/abs/10.1111/geoj.12417

Szesztay, K. (1974). Water balance and water level fluctuations of lakes. *Hydrological Sciences Bulletin*, *19*(1), 73-84. http://www.tandfonline.com/doi/abs/10.1080/02626667409493872

Tachikawa, T., Hato, M., Kaku, M., & Iwasaki, A. (2011). Characteristics of ASTER GDEM version 2. *2011 IEEE International Geoscience and Remote Sensing Symposium*, 3657-3660. https://doi.org/10.1109/IGARSS.2011.6050017

Taghizadeh, E., Ahmadi-Givi, F., Brocca, L., & Sharifi, E. (2021). Evaluation of satellite/reanalysis precipitation products over Iran. *International Journal of Remote Sensing*, *42*(9), 3474-3497. https://doi.org/10.1080/01431161.2021.1875508

Tavares, M. H., Cunha, A. H. F., Motta-Marques, D., Ruhoff, A. L., Cavalcanti, J. R., Fragoso, C. R., Martín Bravo, J., Munar, A. M., Fan, F. M., & Rodrigues, L. H. R. (2019). Comparison of Methods to Estimate Lake-Surface-Water Temperature Using Landsat 7 ETM+ and MODIS Imagery: Case Study of a Large Shallow Subtropical Lake in Southern Brazil. *Water*, *11*(1), Article 1. https://doi.org/10.3390/w11010168

Tedesco, A. M., López-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Pérez-Hämmerle, K.-V., Brancalion, P. H. S., Wilson, K. A., Oliveira, M., Correa, D. F., Ota, L., Morrison, T. H., Possingham, H. P., Mills, M., Santos, F. C., & Dean, A. J. (2023). Beyond ecology: Ecosystem restoration as a process for social-ecological transformation. *Trends in Ecology & Evolution*, *38*(7), 643-653. https://doi.org/10.1016/j.tree.2023.02.007

Tierney, G. L., Faber-Langendoen, D., Mitchell, B. R., Shriver, W. G., & Gibbs, J. P. (2009). Monitoring and evaluating the ecological integrity of forest ecosystems. *Frontiers in Ecology and the Environment*, *7*(6), 308-316. https://doi.org/10.1890/070176

Tilgenkamp, A. (2025, agosto 2). *Theil–Sen estimator [online]. MATLAB Central File Exchange.* https://www.mathworks.com/matlabcentral/fileexchange/34308-theil-sen-estimator

Torres, R. (2023, enero 24). Resistance In Chile's "State Of Exception". *Majority Post*. https://majoritypost.com/resistance-in-chiles-state-of-exception/

Torres, R., Azócar, G., Gallardo, R., & Mendoza, J. (2022). *Water Extractivism and Decolonial Struggles in Mapuche Territory, Chile*. *15*(1).

Torres, R., Azócar, G., Rojas, J., Montecinos, A., & Paredes, P. (2015). Vulnerability and resistance to neoliberal environmental changes: An assessment of agriculture and forestry in the Biobio region of Chile (1974–2014). *Geoforum*, *60*, 107-122. https://doi.org/10.1016/j.geoforum.2014.12.013

Traganos, D., Poursanidis, D., Aggarwal, B., Chrysoulakis, N., & Reinartz, P. (2018). Estimating Satellite-Derived Bathymetry (SDB) with the Google Earth Engine and Sentinel-2. *Remote Sensing*, *10*(6), Article 6. https://doi.org/10.3390/rs10060859

Trenberth, K. E., & Hoar, T. J. (1996). The 1990–1995 El Niño-Southern Oscillation Event: Longest on Record. *Geophysical Research Letters*, *23*(1), 57-60. https://doi.org/10.1029/95GL03602

Troitskaya, Y., Rybushkina, G., Soustova, I., Balandina, G., Lebedev, S., & Kostianoy, A. (2012). Adaptive retracking of Jason-1 altimetry data for inland waters: The example of the Gorky Reservoir. *International Journal of Remote Sensing*, *33*(23), 7559-7578. https://doi.org/10.1080/01431161.2012.685972

UCM. (2024). *Earth Engine Data Catalog: TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces [online]. Merced, University of California Merced.* https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE#bands

University of North Carolina. (2025). *Mediciones en Lagos Red Ciudadana y Satelital*. LOCSS. https://www.locss.org/es

Upreti, G. (2023). Autopoiesis, Organizational Complexity, and Ecosystem Health. En G. Upreti (Ed.), *Ecosociocentrism: The Earth First Paradigm for Sustainable Living* (pp. 91-110). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-41754-2_5

Urrutia, R., Almanza, V., & Woelfl, S. (2022, septiembre 8). *Seminario proyecto: Levantamiento de información limnológica para la propuesta de NSCA de lagos nor-patagónicos* [[Discurso principal]. Seminario en línea.].

US EPA. (2011). *National wetland condition assessment: Field operations manual*.

US EPA. (2025). *Factsheets on Water Quality Parameters*. https://www.epa.gov/awma/factsheets-water-quality-parameters

US EPA, O. (2015, abril 16). *What is the National Lakes Assessment?* [Overviews and Factsheets]. https://www.epa.gov/national-aquatic-resource-surveys/what-national-lakes-assessment

USGS. (2025). *U.S. Geological Survey*. https://www.usgs.gov/

Valdés-Pineda, R., Cañón, J., & Valdés, J. B. (2018). Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals. *Journal of Hydrology*, *556*, 1153-1170. https://doi.org/10.1016/j.jhydrol.2017.01.031

Valdés-Pineda, R., Valdés, J. B., Diaz, H. F., & Pizarro-Tapia, R. (2016, junio 30). *Analysis of spatio-temporal changes in annual and seasonal precipitation variability in South America-Chile and related ocean-atmosphere circulation patterns.* | *EBSCOhost*. https://doi.org/10.1002/joc.4532

Vela, S. R. (2019). Método mayéutica y consultorías filosóficas en el siglo XXI. *Phainomenon*, *18*(2), 141-154. https://doi.org/10.33539/phai.v18i2.1745

Vera, R., & Rosner, C. (2020). *Recopilación y análisis de antecedentes para la revisión de la Norma Secundaria de Calidad Ambiental del lago Llanquihue*. ResearchGate. https://doi.org/10.13140/RG.2.2.29431.80801

Vergara Díaz, G., Vázquez, V. S., & Herrera Machuca, M. Á. (2018). Análisis del ambio temporal y espacial del uso del suelo en la región Centro-sur de Chile. *Ciência Florestal*, *28*, 1831-1844. https://www.scielo.br/j/cflo/a/rtg7y6cGShDvQkMjWL7k47Q/?lang=es&format=html&stop=next

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). *A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index*. https://doi.org/10.1175/2009JCLI2909.1

Vlasova, T., Petrov, A. N., & Volkov, S. (2021). Rethinking Sustainability Monitoring in the Arctic by Linking Resilience and Sustainable Development in Socially-Oriented Observations: A Perspective. *Sustainability*, *13*(1), Article 1. https://doi.org/10.3390/su13010177

Voulvoulis, N., Giakoumis, T., Hunt, C., Kioupi, V., Petrou, N., Souliotis, I., Vaghela, C., & binti Wan Rosely, WIH. (2022). Systems thinking as a paradigm shift for sustainability transformation. *Global Environmental Change*, *75*, 102544. https://www.sciencedirect.com/science/article/pii/S0959378022000826

Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., & Bierkens, M. F. P. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, *37*(20). https://doi.org/10.1029/2010GL044571

Wadoux, A. M. J.-C., & Minasny, B. (2024). Some limitations of the concordance correlation coefficient to characterise model accuracy. *Ecological Informatics*, *83*, 102820. https://doi.org/10.1016/j.ecoinf.2024.102820

Wakana, I., Kadono, Y., Urabe, J., Tamura, Y., Suzuki, Y., Yamada, H., Oyama, Y., Wada, K., Hasegawa, T., & Ohara, M. (2023). Varying stages of ecological succession in lakes subdivided by volcanic eruptions at Akan Caldera, Japan. *Hydrobiologia*, *850*(18), 3919-3933. https://doi.org/10.1007/s10750-023-05231-5

Wang, H., Qi, Y., Lian, X., Zhang, J., Yang, R., & Zhang, M. (2022). Effects of climate change and land use/cover change on the volume of the Qinghai Lake in China. *Journal of Arid Land*, *14*(3), 245-261. https://doi.org/10.1007/s40333-022-0062-4

Warner, S., Blanco Ramírez, S., de Vries, S., Marangu, N., Ateba Bessa, H., Toranzo, C., Imaralieva, M., Abrate, T., Kiminta, E., Castro, J., de Souza, M. L., Ghaffar Memon, A., Loiselle, S., & Juanah, M. S. E. (2024). Empowering citizen scientists to improve water quality: From monitoring to action. *Frontiers in Water*, *6*. https://doi.org/10.3389/frwa.2024.1367198

Westra, L., & Lemons, J. (2012). *Perspectives on Ecological Integrity*. Springer Science & Business Media.

Wetzel, R. G. (2001). *Limnology: Lake and River Ecosystems*. Gulf Professional Publishing.

Williams, J. (2021). *Climate change is racist: Race, privilege and the struggle for climate justice*. Icon Books. https://books.google.es/books?hl=es&lr=&id=RIQiEAAAQBAJ&oi=fnd&pg=PP8&dq=Williams,+J.+(2021).+Climate+change+is+racist:+Race,+privilege+and+the+struggle+for+climate+justice.+Icon+Books.&ots=NWw2BQCCgc&sig=7BuVe4PrQpNz7d1MptUcKTYDbj4

Willmott, C. J. (1981). On the Validation of Models. *Physical Geography*, *2*(2), 184-194. https://doi.org/10.1080/02723646.1981.10642213

Winkler, K., Fuchs, R., Rounsevell, M., & Herold, M. (2021). Global land use changes are four times greater than previously estimated. *Nature Communications*, *12*(1), 2501. https://www.nature.com/articles/s41467-021-22702-2

Winter, T. C. (1981). Uncertainties in Estimating the Water Balance of Lakes. *JAWRA Journal of the American Water Resources Association*, *17*(1), 82-115. https://doi.org/10.1111/j.1752-1688.1981.tb02593.x

WISDOM. (2025). *Objectives of the WISDOM Project*. https://wisdom.eoc.dlr.de/en/content/objectives-wisdom-project.html

WMO. (2025). *WMO Information System (WIS)*. https://old.wmo.int/extranet/pages/prog/www/WIS/

WMOa. (2025). *Observing Systems Capability Analysis and Review Tool (OSCAR)*. https://oscar.wmo.int/surface/#/

Wolodarsky-Franke, A., & Díaz, S. (2011). Cordillera de Nahuelbuta. *Reserva Mundial de Biodiversidad. Valdivia, Chile: WWF*.

Wongchuig, S., Carlo Espinoza, J., Condom, T., Junquas, C., Sierra, J. P., Fita, L., Sörensson, A., & Polcher, J. (2023). Changes in the surface and atmospheric

water budget due to projected Amazon deforestation: Lessons from a fully coupled model simulation. *Journal of Hydrology*, *625*, 130082. https://doi.org/10.1016/j.jhydrol.2023.130082

Woods, S. (2025). How citizen science can help to solve the global freshwater crisis. *Nature*, *644*(8077), 582-582. https://doi.org/10.1038/d41586-025-02614-7

Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews Earth & Environment*, *1*(8), 388-403. https://doi.org/10.1038/s43017-020-0067-5

Woolway, R. I., Sharma, S., & Smol, J. P. (2022). Lakes in Hot Water: The Impacts of a Changing Climate on Aquatic Ecosystems. *BioScience*, *72*(11), 1050-1061. https://doi.org/10.1093/biosci/biac052

Woolway, R. I., Tong, Y., Feng, L., Zhao, G., Dinh, D. A., Shi, H., Zhang, Y., & Shi, K. (2024). Multivariate extremes in lakes. *Nature Communications*, *15*(1), 4559. https://doi.org/10.1038/s41467-024-49012-7

Wu, J., Li, W., Du, H., Wan, Y., Yang, S., & Xiao, Y. (2025). Nonlinear responses of coupled socioecological systems to land use and climate changes in the Yangtze river basin. *Scientific Reports*, *15*(1), 6940. https://doi.org/10.1038/s41598-025-92084-8

Wurtsbaugh, W. A., Paerl, H. W., & Dodds, W. K. (2019). Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *WIREs Water*, *6*(5), e1373. https://doi.org/10.1002/wat2.1373

Xu, J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Xu, W. (2022). Ecological Integrity Evaluation of Organically Evolved Cultural Landscape. *Mobile Information Systems*, *2022*(1), 9554359. https://doi.org/10.1155/2022/9554359

Xu (徐菊英), J., Hu (胡春迪), C., Yang (杨崧), S., Lian (连涛), T., & Cai (蔡文炬), W. (2025). Unfolding the differences in two types of ENSO indices with various definitions: A systematic carding with the same criteria. *Earth-Science Reviews*, *264*, 105076. https://doi.org/10.1016/j.earscirev.2025.105076

Yang, J., & Du, X. (2017). An enhanced water index in extracting water bodies from Landsat TM imagery. *Annals of GIS*, *23*(3), 141-148. https://doi.org/10.1080/19475683.2017.1340339

Yang, Xu, M., Li, R., Zhang, L., & Deng, Q. (2020). Estimating the ecological water levels of shallow lakes: A case study in Tangxun Lake, China. *Scientific Reports*, *10*(1), 5637. https://doi.org/10.1038/s41598-020-62454-5

Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J.-F., Wada, Y., & Berge-Nguyen, M. (2023). Satellites reveal widespread decline in global lake water storage. *Science*, *380*(6646), 743-749. https://doi.org/10.1126/science.abo2812

Zelený, J., Mercado-Bettín, D., & Müller, F. (2021). Towards the evaluation of regional ecosystem integrity using NDVI, brightness temperature and surface heterogeneity. *Science of The Total Environment*, *796*, 148994. https://www.sciencedirect.com/science/article/pii/S0048969721040663

Zhang, M., Lee, H., SHUM, C. K., Alsdorf, D., Schwartz, F., Tseng, K.-H., Yi, Y., Kuo, C.-Y., Tseng, H.-Z., Braun, A., Calmant, S., Filizola, N., & Seyler, F. (2010). Application of retracked satellite altimetry for inland hydrologic studies. *International Journal of Remote Sensing*, *31*(14), 3913-3929. https://doi.org/10.1080/01431161.2010.483495

Zhao, G., Li, Y., Zhou, L., & Gao, H. (2022). Evaporative water loss of 1.42 million global lakes. *Nature Communications*, *13*(1), 3686. https://doi.org/10.1038/s41467-022-31125-6

Zhao, Y., Feng, D., Yu, L., Wang, X., Chen, Y., Bai, Y., Hernández, H. J., Galleguillos, M., Estades, C., Biging, G. S., Radke, J. D., & Gong, P. (2016). Detailed dynamic land cover mapping of Chile: Accuracy improvement by integrating multi-temporal data. *Remote Sensing of Environment*, *183*, 170-185. https://www.sciencedirect.com/science/article/pii/S0034425716302188

Zhou, J., Leavitt, P. R., Rose, K. C., Wang, X., Zhang, Y., Shi, K., & Qin, B. (2023). Controls of thermal response of temperate lakes to atmospheric warming. *Nature Communications*, *14*(1), 6503. https://doi.org/10.1038/s41467-023-42262-x

Zhu, J., Peng, S., Shen, X., Lin, Z., Gong, L., Zhang, R., & Huang, B. (2024). Multiple scale impacts of land use intensity on water quality in the Chishui river source area. *Ecological Indicators*, *166*, 112396. https://doi.org/10.1016/j.ecolind.2024.112396

Zhu, L., Ju, J., Qiao, B., Liu, C., Wang, J., Yang, R., Ma, Q., Guo, L., & Pang, S. (2025). Physical and biogeochemical responses of Tibetan Plateau lakes to climate change. *Nature Reviews Earth & Environment*, *6*(4), 284-298. https://doi.org/10.1038/s43017-025-00650-5