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Agotamiento de las Aguas Subterráneas y su relación con la Agricultura y los Ecosistemas Dependientes en cuencas del Centro-Norte de Chile

Tesis para optar al grado de Doctor en Ciencias Ambientales con mención en Sistemas Acuáticos Continentales

Iongel Durán Llacer
Concepción-Chile
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Profesor Guía: José Luis Arumí Ribera
Dpto. de Recursos Hídricos, Facultad de Ingeniería Agrícola
Centro Fondap CRHIAM
Universidad de Concepción

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Dra. José Luis Arumí Ribera
Profesor Guía
Facultad de Ingeniería Agrícola
Universidad de Concepción
____

Dr. Octavio Rojas Vilches
Miembro Comité de Tesis
Facultad de Ciencias Ambientales
Universidad de Concepción
____

Dr. Mauricio Aguayo Arias
Miembro Comité de Tesis
Facultad de Ciencias Ambientales
Universidad de Concepción
____

Dr. Ricardo Oyarzún Lucero
Evaluador Externo
Departamento Ingeniería de Minas
Universidad de La Serena
____

Concepción-Chile
2021

A Dios
y a todos mis seres queridos

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Reseña Currículum Vitae

Iongel Durán Llacer

- Licenciado en Geografía (Honores), Universidad de La Habana, Cuba (2008-2013).

- Diplomado en Geografía, Medio ambiente y Ordenamiento Territorial, Universidad de La Habana, Cuba (2015-2017).

- Doctorado en Ciencias Ambientales con mención en Sistemas Acuáticos Continentales, Universidad de Concepción, Chile (2017-2021).

Publicaciones

Relacionadas con el proyecto de doctorado

Duran-Llacer, I.; Arumí, J.L.; Arriagada, L.; Aguayo, M.; Rojas, O.; González-Rodríguez, L.; Rodríguez-López, L.; Martínez-Retureta, R.; Oyarzún, R.; Sudhir, K. (**En revisión**). A new method to map potential groundwater-dependent ecosystem zones in semi-arid environments: A case study in Chile. *Science of the Total Environment*. WoS.

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Participación en eventos científicos

Duran-Llacer, I.; Arumí, J.L.; Arriagada, L.; Aguayo, M.; Rojas, O.; Oyarzún, R.; and Sudhir, K. Mapeo de ecosistemas dependientes de agua subterránea mediante criterio de experto, Teledetección y SIG. *XVIII Encuentro de Geógrafos de América*

Latina EGAL 2021, que será celebrado online en Buenos Aires, Argentina. Noviembre, 2021. (Oral).

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Duran-Llacer, I; Rodríguez, G.; and Lapinel, B. Number of days with rain and atmospheric circulation during extreme drought events in Central Cuba. *Coloquio Aportes de la UdeC en la Conferencia Internacional sobre Monitoreo Espacial del Agua*, celebrado en el Centro de Ciencias Ambientales EULA, Universidad de Concepción el 12 de Abril del 2018. (Oral).

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Estancias académicas

Earth Science Department, School of Geographical Sciences, University of Bristol, Reino Unido, noviembre, 2019- febrero, 2020.

Líneas e intereses de Investigación

Principal: Cambio global, sociedad y agua

Secundaria: Biodiversidad, servicios ecosistémicos y agua

Experiencia en Docencia

Desde el 2013 al 2017 impartió docencia en la carrera de Geografía, Universidad de La Habana, en las asignaturas de Meteorología-Climatología, Meteorología Tropical y Prácticas de Campo, alcanzando la categoría de Profesor Instructor. A partir del 2017 realizó colaboraciones académicas o ayudantías en la carrera de Ingeniería Ambiental de la Universidad de Concepción en asignaturas como Introducción a la Ingeniería Ambiental, Sistemas Territoriales I, Ecología Acuática, Conservación de la Biodiversidad, Gestión de Cuencas Hidrográficas y Riesgos Ambientales. En la asignatura de Ecología, carrera Ingeniería en Energía y Sustentabilidad de la Universidad San Sebastián, ha colaborado como profesor invitado. Además, ha dictado charlas a estudiantes en colegios como parte del programa Explora de ANID.

Becas y Reconocimientos

Editor's Choice Article* de la revista *Water* por el paper: **Duran-Llacer, I**.; Munizaga, J.; Arumí, J.L.; Ruybal, C.; Aguayo, M.; Sáez, K.; Arriagada, L.; Rojas, O. Groundwater Depletion in Chile´s Ligua and Petorca Watersheds through an Interdisciplinary Approach. *Water* 2020, Volume 12, Issue 9, 2446. doi:10.3390/w12092446 (08/2020). WoS

Premio Best Presentation and Excellent Paper Award en la International Conference on Environmental Science and Development (ICESD), Oxford, United Kingdom, 19 al 21 de enero, 2020.

Gastos de Operación y Pasantía para Estudiantes de Doctorado en Chile de CONICYT, convocatoria 2019.

Beca Asistencia a Eventos para Estudiantes de Doctorado en Chile de CONICYT, convocatoria 2019.

Premio categoría Poster en el Primer encuentro de estudiantes e investigadores postdoctorales CRHIAM, abril del 2019.

Beca de la Comisión Nacional de Investigación Científica y Tecnológica CONICYT 2017, Chile. ANID.

Mejor graduado docentemente, carrera de Geografía, Facultad de Geografía, Universidad de la Habana, 2013.

Título de Oro de Licenciado en Geografía (Honores), Facultad de Geografía, Universidad de la Habana, 2013.

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Glosario de términos

GW: Aguas Subterráneas (siglas en inglés)

SPI: Índice Estandarizado de Precipitación

NDVI: Índice de Vegetación de Diferencia Normalizada

NDWI: Índice de Agua de Diferencia Normalizada

SAVI: Índice de Vegetación Ajustado al Suelo

MSAVI: Índice de Vegetación Ajustado al Suelo Modificado

EVI: Índice de Vegetación Mejorado

LULCC: Cambio del uso y la cobertura del suelo

LULC: Uso y cobertura del suelo

GW rights: Derechos de Aguas Subterráneas

ND: Nuevo derecho de aprovechamiento de aguas subterráneas

VPC: Cambio del Punto de Captación del derecho de agua subterránea dentro de un mismo sector de aprovechamiento

NR: Derecho regularizado a través de una inscripción del derecho

UA: Usuarios antiguos con derechos de aguas subterráneas que han mantenido su derecho a través de una concesión de agua o transacción

(CR)^2: Centro de Ciencia del Clima y Resiliencia

CR2MET: Datos grillados a 0.05° de lluvia y temperatura en Chile del (CR)^2

DGA: Dirección General de Aguas

INE: Instituto Nacional de Estadísticas

CNR: Comisión Nacional de Riego

MOP: Ministerio de Obras Públicas

CIREN: Centro de información de Recursos Naturales

ODEPA: Oficina de Estudios y Políticas Agrarias

CNAP: Comité Nacional de Áreas Protegidas

MMA: Ministerio del Medio Ambiente

MODATIMA: Movimiento de Defensa del Agua, la Tierra y el Medio Ambiente

DEM: Modelo Digital de Elevación

MODIS: Espectrorradiómetro de Imágenes de Resolución Moderada. Satélite con imágenes de 250 m de resolución espacial.

GEE: Google Earth Engine

TM: Thematic Mapper sensor

ETM+: Enhanced Thematic Mapper sensor

OLI: Operational Land Imager sensor

SLC: Scan Line Corrector

USGS: Servicio Geológico de los Estados Unidos

UNEP: Programa de las Naciones Unidas para el Medio Ambiente

R: Lluvia

Ai: Índice de Aridez

ETP: Evapotranspiración Potencial

GDE: Ecosistemas Dependientes de las Aguas Subterráneas

PGDEZ: Zonas Potenciales de Ecosistemas Dependientes de las Aguas Subterráneas (siglas en Inglés)

GIS: Sistemas de Información Geográficas

Dd: Densidad de Drenaje

Ld: Densidad de Lineamientos

TPI: Índice de Posición Topográfica

Fa: Acumulación de Flujo

Ct: Curvatura

TRI: Índice de Rugosidad Topográfica

TWI: Índice de Humedad Topográfica

OMM: Organización Meteorológica Mundial

Resumen

El agua subterránea (GW) es la principal fuente de agua dulce no congelada del planeta y, en muchas áreas semiáridas, es la única fuente de agua disponible durante los períodos de estiaje. Su uso se ha intensificado en las últimas décadas y existe un creciente riesgo de agotamiento a nivel mundial. En el Centro-Norte de Chile, zona de alta producción agrícola, se ha producido un agotamiento de las GW como resultado de las condiciones semiáridas y la alta demanda de agua, lo que ha desencadenado importantes conflictos sociales, algunos por la sequía y otros por las prácticas del agronegocio en el contexto de un modelo privado de gestión hídrica. No obstante, debido a la alta demanda de GW, la integridad ecológica de muchos ecosistemas que dependen estrictamente de este recurso también puede verse afectada, en particular aquellos conocidos como Ecosistemas Dependientes de las Aguas Subterráneas (GDE). Por tanto, el objetivo principal de esta investigación es evaluar la relación entre el agotamiento de las GW con los cambios en la agricultura y los ecosistemas dependientes en las cuencas La Ligua y Petorca, Región de Valparaíso, Chile.

La relación entre las GW y la agricultura fue evaluada a través del Índice Estandarizado de Precipitación (SPI), el Índice de Vegetación de Diferencia Normalizada (NDVI), el cambio del uso del suelo entre 2002 y 2017, los derechos otorgados de las GW y los datos del nivel del agua en pozos. Estas variables empleadas fueron analizadas estadísticamente mediante correlaciones, correlaciones cruzadas, test de tendencia y análisis de conglomerados. El análisis satelital general se desarrolló en la plataforma Google Earth Engine (GEE). Posteriormente, un nuevo método geoespacial con un enfoque integrado y temporal fue desarrollado para mapear Zonas Potenciales de Ecosistemas Dependientes de las Aguas Subterráneas (PGDEZ en inglés), con el objetivo de analizar los cambios espacio-temporales de los GDE ante el nivel cambiante de las GW. Se realizó una encuesta a expertos para asignar peso a distintos parámetros geoespaciales considerados como predictores de la presencia de GDE. Luego 14 parámetros fueron reclasificados y normalizados en una escala de 1 a 5 según la alta o baja probabilidad de encontrar estos ecosistemas (muy alta, alta, media, baja y muy baja). El mapeo se llevó a cabo mediante la herramienta de superposición ponderada en el ArcGIS 10.8.1 y la validación se realizó mediante trabajo de campo. Por último, se analizaron datos de GW, lluvia y NDVI.

Se demostró que el GW disminuyó significativamente (en el 75% de los pozos) y que la sequía hidrológica ha sido moderada pero muy prolongada. El área de cultivo del palto en La Ligua aumentó significativamente (2 623 ha), con respecto a otras áreas agrícolas, mientras que en Petorca disminuyó en 128 ha. En ambas cuencas las zonas de aumento del palto coincidieron con las zonas de mayor disminución de las GW y en Petorca se presentó el mayor aumento de la cantidad de embalses. Las correlaciones GW-lluvia fueron bajas, mientras con el NDVI resultaron altas, y los derechos de las GW se otorgaron continuamente a pesar de la sequía. Estos resultados confirmaron que el agotamiento de los acuíferos fue influenciado principalmente por factores antrópicos debido a la sobreexplotación de las GW como consecuencia del aumento de la demanda de agua por la agricultura y la falta de gestión hídrica. Por otra parte, los parámetros geoespaciales de mayor peso asignado por los expertos (N=26) con respecto a la probabilidad de presencia de un GDE fueron la geología, la lluvia, el uso del suelo, la geomorfología y el NDVI. Los mapas de las PGDEZ entre el 2002 y el 2017 mostraron un descenso en la superficie de las zonas “muy altas” y “altas” (0.72 y 7.43 %, respectivamente). Los parámetros temporales más sensibles en el análisis multicriterio fueron la lluvia y el cambio del uso del suelo, siendo la lluvia el de ligeramente mayor influencia. Se demostró además que los ecosistemas identificados como GDE disminuyeron o fueron afectados mayormente por el agotamiento de los acuíferos (NDVI-GW, r Pearson ≥ 0.74), respecto a la lluvia y los cambios antrópicos.

Palabras claves: aguas subterráneas, sequía, cambio del uso del suelo, NDVI, derechos de aguas subterráneas, GDE, análisis multicriterio, opinión de experto, SIG, Teledetección, cuencas La Ligua y Petorca.

Abstract

Groundwater (GW) is the primary source of unfrozen freshwater on the planet and in many semi-arid areas, it is the only source of water available during low-water periods. Its use has intensified in recent decades and there is a growing risk of depletion globally. In north-central Chile, an area of high agricultural production, there has been a GW depletion as a result of semi-arid conditions and high water demand, which has unleashed major social conflicts, some due to drought and others due to agribusiness practices against the backdrop of a private water management model. However, due to the GW high demand , the ecological integrity of some ecosystems that host little-known biodiversity is affected, specifically those known as Groundwater Dependent Ecosystems (GDE). Therefore, the main objective of this research is to evaluate the relationship between GW depletion with changes in agriculture and dependent ecosystems in the La Ligua and Petorca watersheds, Valparaíso Region, Chile.

The relationship between GW and agriculture was evaluated through the Standardized Precipitation Index (SPI), the Normalized Difference Vegetation Index (NDVI), the land use change between 2002 and 2017, the GW rights granted and well water level data. These variables used were statistically analyzed using correlations, cross-correlations, trend tests, and cluster analysis. The general satellite analysis was worked on the Google Earth Engine (GEE) platform. Subsequently, a new geospatial method was developed with an integrated and temporal approach to map Groundwater-Dependent Ecosystem Potential Zones

(GDEPZ), with the aim of analyzing the spatio-temporal changes of the GDEs against the changing level of the GW. A survey of experts was carried out to assign weight to different geospatial parameters considered predictors of GDE presence. Then, fourteen parameters were reclassified and normalized on a scale from 1 to 5 according to the high or low probability to find GDE (very high, high, medium, low and very low). Mapping across the weighted overlay tool in ArcGIS 10.8.1 was done and, the validation through field work was possible. Finally, GW, rainfall, and NDVI data were analyzed.

It was shown that GW decreased significantly (in 75% of the wells) and that the hydrological drought has been moderate but very prolonged. The avocado-growing area in Ligua increased significantly (2,623 ha), with respect to other agricultural areas, while in Petorca, it decreased by 128 ha. In both basins, the areas of avocado increase coincided with the areas with the greatest decrease in GW and in Petorca there was the greatest increase in the numbers of reservoirs. The GW-rainfall correlations were low, while with the NDVI they were high, and GW rights were granted continuously despite the drought. These results confirmed that aquifers depletion was mainly influenced by anthropic factors due to GW overexploitation as a consequence of the increase in water demand by agriculture and a lack of water management. On the other hand, the geospatial parameters with the highest weight assigned by the experts (N = 26) with respect to the probability of presence of a GDE were geology, rainfall, land use, geomorphology and NDVI. The GDEPZ maps between 2002 and 2017 showed a decrease in the "very high" and "high" areas surface (0.72 and 7.43%, respectively). The most sensitive temporal parameters in the multicriteria analysis were rain and land use change, with rain having a slightly greater influence. It was also demonstrated that the ecosystems identified as GDE decreased or were mainly affected by the aquifer's depletion (NDVI-GW, Pearson r ≥ 0.74), respect to rainfall and anthropic changes.

Keywords: groundwater, drought, land use change, NDVI, groundwater rights, GDE, multi-criteria analysis, expert opinion, GIS, Remote Sensing, La Ligua and Petorca watersheds.

CAPÍTULO I. INTRODUCCIÓN

I.1 Agotamiento de las aguas subterráneas a nivel mundial

El agua subterránea (GW) es un recurso muy valioso ya que representa el 96% del agua dulce no congelada del planeta (Eamus et al., 2015; Mossa et al., 2019). Es la fuente principal de agua para el uso humano y las actividades agrícolas e industriales en regiones áridas y semiáridas (Abou Zaki et al., 2019; Feng et al., 2018; Liu et al., 2021). Se estima que suministra el 36% del agua potable, el 42% del agua de riego y el 24% del agua industrial en todo el mundo (Ashraf et al., 2021; Dangar et al., 2021; Mossa et al., 2019). Su uso se ha intensificado en las últimas décadas y existe un creciente riesgo de agotamiento en la mayor parte del mundo, ya que se estima que el 20% de los acuíferos están siendo sobreexplotados (Mossa et al., 2019). Esta sobreexplotación se debe a la escasez de agua como resultado del aumento desmedido de la demanda, respecto al real suministro natural de GW y a la falta de una gestión sostenible de las GW (Chen et al., 2020). Por tanto, este agotamiento puede mitigarse a través de una eficiente gestión de las GW, ya que es la herramienta fundamental capaz de lograr un equilibrio entre la disponibilidad y la extracción de agua, asegurando su protección y uso eficiente para las actuales y futuras generaciones (Alley and Leake, 2004; Mossa et al., 2019).

Se ha estimado que el agotamiento subterráneo mundial aumentó de 126 a 283 km^3/a entre 1960 y 2000, y que la extracción global aumentó en 422 km^3/a (Frappart and Ramillien, 2018; Wada et al., 2010). Se ha estimado que la huella de GW (área requerida para sostener el uso del agua subterránea y los servicios ecosistémicos dependientes del GW) mundial actual es 3.5 veces mayor que el área real de un acuífero (Dangar et al., 2021). En Irán el agotamiento estimado actual supera los 74 km^3/a (Ashraf et al., 2021) y en la India el nivel freático disminuyó aproximadamente de un 30% a un 75 % entre el 2000 y el 2019 (Sidhu et al., 2021). En gran parte de los Estados Unidos (suroeste y centro-sur) el GW ha disminuido en 90 km^3/a (Rateb et al., 2020). Por su parte en América Latina se ha observado una tendencia negativa de las GW en los últimos años con una tasa anual de anomalías de -0.24 mm/a, lo que sugiere un agotamiento acuífero por causas naturales como la sequía y/o aumento exponencial de las actividades agrícolas e industriales (Khaki and Awange, 2019).

La sequía se manifiesta en el sistema hidrológico en diferentes escalas espacio-temporales y contribuye a la disminución del almacenamiento del acuífero, ya que afecta la recarga y los niveles de agua, de manera que también puede afectar la actividad agrícola (Lee et al., 2019). Además de la sequía, el cambio climático global, el cambio acelerado del uso de la tierra (expansión agrícola y urbana), el riego agrícola y la construcción de embalses pueden también generar una disminución de la recarga y el almacenamiento de GW (Lamichhane and Shakya, 2019; Lee et al., 2019, 2018), principalmente en las regiones semiáridas (Moiwo and Tao, 2014).

La tasa global de captación de GW se ha duplicado en los últimos decenios, generando una amenaza importante para la salud ecológica de muchos ecosistemas y para el abasto de agua potable a la población mundial y a la agricultura, lo que puede acontecer en disminución de la productividad agrícola (Gemitzi and Lakshmi, 2018; Tang et al., 2017).

I.2 Aguas subterráneas y agricultura

La explotación de los recursos hídricos subterráneos, incluido el desarrollo de extensos sistemas de riego, a menudo ha dado lugar a una extracción excesiva, lo que ha provocado una reducción drástica de los niveles de GW y el almacenamiento asociado. Este uso excesivo puede volverse insostenible (Dalin, 2021). El riego contribuyente a la escasez física de agua a nivel mundial, ya que impulsa el 70 % de la demanda bruta mundial de agua, y aproximadamente el 40% del consumo de agua para la agricultura proviene ahora de las GW, y esta proporción ha aumentado rápidamente en las últimas décadas (Dalin, 2021; Dangar et al., 2021). Por lo que la agricultura de regadío es el principal elemento de extracción y consumo de las GW (Dey et al., 2017). La explotación de las GW se debe principalmente a la rápida expansión de las tierras de regadío para satisfacer las necesidades de la demanda alimentaria de la creciente población (Dangar et al., 2021). La población y el crecimiento económico continúan aumentando la demanda mundial de alimentos y se espera que, para 2050, necesitemos un 60% más de producción de alimentos que en 2010. En consecuencia, se espera que continúe aumentando el riego (Dalin, 2021). Mundialmente se han realizado grandes inversiones en pozos, se han tecnificado los sistemas de regadío, han surgido grandes agro-economías y todo a base de los recursos hídricos subterráneos (Siebert et al., 2010).

El GW es una fuente importante de riego en la mayoría de los países de América del Sur (Khaki and Awange, 2019). En el Medio Oriente el 85% del uso del agua se utiliza exclusivamente para el riego (Ashraf et al., 2021) y en la India, el área regada aumentó del 58.8% al 60.4% de 1961 a 2016 (Dangar et al., 2021). La superficie de riego con GW representa en el Sur de Asia un 57%, en Oriente Medio y Norte de África un 43 %, en Estados Unidos un 60% y en América Latina un 18% (Partnership Global Water, 2012; Siebert et al., 2010), mientras en Chile el 49% de los 88 m^3 de utilización efectiva de las GW es empleada en la agricultura (Banco Mundial, 2011). A nivel mundial, el consumo de agua para la agricultura está aumentando y se pronostica que sea de 584 km^3/a durante el período 2000-2025. Se estimó además, que la evapotranspiración de las tierras agrícolas es de 7 130 km^3 y se prevé que aumente entre un 60% y un 90% para 2050 si no aumenta la productividad del agua.

El conocimiento inclusivo del uso de GW y los sistemas de producción de cultivos es esencial para que los administradores y los encargados de formular políticas mejoren la gestión del GW en áreas de escasez hídrica (Mainuddin et al., 2020). Estas conexiones agregan una capa de complejidad a la tarea de establecer proyecciones futuras del agotamiento de las GW a nivel mundial (Dalin, 2021). Como es evidente, los principales esfuerzos de conservación y manejo de las GW se enfocan en su protección para los diferentes usos humanos, principalmente el agrícola (Kløve et al., 2014b). No obstante, la integridad ecológica de muchos ecosistemas que dependen del aporte de las GW y albergan una biodiversidad poco conocida, también puede verse afectada con el agotamiento de este recurso, en particular aquellos conocidos como Ecosistemas Dependientes de las Aguas Subterráneas (GDE).

I.3 Ecosistemas Dependientes de las Aguas Subterráneas (GDE)

El GW juega un papel integral en el sustento de ciertos tipos de ecosistemas acuáticos, terrestres y costeros, y sus paisajes asociados (Aslam et al., 2018). Proporciona un flujo de entrada que mantiene las condiciones físico-químicas necesarias para la flora y fauna que sustenta (Howard and Merrifield, 2010). Suministra el flujo base a fines del verano para muchos ríos y es la única fuente para manantiales y ecosistemas que albergan una biodiversidad importante pero muchas veces poco conocida (Kløve et al., 2014b). Por tanto, el GW es un factor relevante en la integridad ecológica de muchos ecosistemas como los Ecosistemas Dependientes de las Aguas Subterráneas (GDE) (Kløve et al., 2014b; Liu et al., 2021).

Los GDE pueden definirse como ecosistemas para los cuales la composición, estructura y función actual depende del suministro de las GW, o sea, ecosistemas naturales, dinámicos y complejos que requieren acceso al GW para satisfacer todas o algunas de sus necesidades, ya sea de manera permanente o intermitente, a fin de mantener sus comunidades de plantas y animales, procesos y servicios ecosistémicos (Doody et al., 2019; Liu et al., 2021). Los GDE son un componente vital pero aún no completamente entendido del entorno natural. En muchos casos, las GW hacen una contribución importante pero poco documentada a diversos ecosistemas acuáticos y terrestres, como ríos, incluyendo hábitats acuáticos, hiporreicos y ribereños, humedales y manantiales, árboles y arbustos, praderas, así como ecosistemas estuarinos y costeros (Doody et al., 2017; Howard and Merrifield, 2010; Liu et al., 2021). Estos ecosistemas dependientes proporcionan hábitats para muchas especies sensibles principalmente en ambientes áridos y semiáridos (Huntington et al., 2016).

Estos ecosistemas dependen del GW cercana a la superficie (Huntington et al., 2016) por lo que el descenso de las GW puede traerle efectos devastadores (Doody et al., 2019). Estos efectos no solo provienen de la extracción de agua para riego y consumo humano, sino también de la reducción de la recarga, como resultado de la disminución de las precipitaciones y del cambio en el uso del suelo (Doody et al., 2017). Por tales motivos la salud ecológica de la biota de estos ecosistemas puede alterarse ya que se afecta el transporte de iones disueltos, nutrientes y materia orgánica. Por ende, se puede afectar la extraordinaria biodiversidad endémica y una proporción de especies reliquias, incluidos microorganismos altamente especializados (Kløve et al., 2011b).

Los principales esfuerzos de conservación y manejo de las GW se enfocan en su protección para los diferentes usos humanos, pero el enfoque en los GDE ha sido más bien limitado (Kløve et al., 2014). Se requieren grandes esfuerzos para comprender la estrecha relación entre las GW y los ecosistemas que sustentan, como un indicador indispensable para vincular tanto las necesidades hídricas humanas como las ecológicas (Pérez Hoyos et al., 2016). Estas necesidades aparecen como usos distintos, pero deben manejarse de manera integrada y multidisciplinariamente (Kløve et al., 2011b; Zurek et al., 2015). No obstante, para caracterizar el grado de dependencia del GW, la respuesta ecológica y su efectiva gestión, primero es necesario comprender la ubicación y extensión de estos ecosistemas (Marques et al., 2019; Pérez Hoyos et al., 2016).

I.4 Agotamiento de las aguas subterráneas en el Centro-Norte de Chile

En Chile, el uso de GW ha aumentado a un ritmo exponencial en las últimas décadas y aunque la preocupación por la sostenibilidad a largo plazo ha ganado importancia, la política de GW para abordar las pérdidas aún sigue en etapa precaria (Donoso et al., 2020). Chile supera la media mundial en disponibilidad hídrica pero esta distribución es desigual, pues se concentra en la parte sur. La disponibilidad de GW es menor a la media mundial y los sectores hidrológicos de aprovechamiento de GW en el centro y norte se encuentran por debajo de la demanda, siendo decretadas varias zonas como áreas de restricción (Banco Mundial, 2011; MOP and DGA, 2018). Muchas actividades agrícolas en esta zona, se basan en el uso de fuentes subterráneas debido a las condiciones semiáridas (Ayala et al., 2014; Donoso et al., 2020). Por tanto, la mayor demanda en la región central se estima para el sector agrícola, seguido por el agua potable e industrial (Donoso et al., 2020). A todo esto se la suma un privatizado sistema de gestión que no garantiza el uso y asignación eficiente de este recurso (Buzolic et al., 2021).

El modelo de gestión del agua en Chile se encuentra entre los más privatizados y mercantilizados del mundo (Bolados et al., 2017). Este sistema de asignación de agua está regulado por un mercado de derechos de uso, en el cual los derechos son otorgados por el Estado a usuarios privados a perpetuidad y sin costo. Como los derechos se definen como propiedad privada, pueden transferirse, comprarse o alquilarse libremente como cualquier otro bien privado y cada propietario puede canjear sus derechos a precios de mercado (Buzolic et al., 2021); por tanto, los mecanismos públicos de regulación y supervisión son bastante limitados (Muñoz et al., 2020) y este sistema no asegura la existencia de infraestructura tangible e intangible para el correcto funcionamiento del modelo (Buzolic et al., 2021; Hearne and Donoso, 2014). Esto ha resultado en una creciente desigualdad con respecto al acceso al agua y los conflictos sociales por los recursos hídricos han ganado la atención política (Budds, 2012; Panez-Pinto et al., 2017).

Muchos acuíferos en la actualidad se encuentran bajo tensión debido a que las extracciones para el uso agrícola superan la recarga (Donoso et al., 2020). De hecho, muchas cuencas hidrográficas en esta zona, incluidas las cuencas de La Ligua y Petorca en la Región de Valparaíso, presentan un alto grado de explotación que en algunos casos ha superado los niveles de sostenibilidad del acuífero, más aún si se consideran períodos prolongados de sequía (Ayala et al., 2014; Celedón, 2019). La provincia de Petorca, ubicada en esta área, fue declarada zona de escasez hídrica [1] en 1997 (DGA-MOP, 2019; Muñoz et al., 2020) y zona de restricción de GW [2] en 2014 (DGA-MOP, 2019). Este territorio ha dado un cambio histórico hacia las plantaciones de paltos *Persea americana* (gran consumidor de agua ya que requieren riego durante todo el año), convirtiéndose en exportadora mundial (60%), llevando a una tecnificación de los sistemas de regadío, al monocultivo y el sobreotorgamiento de los derechos del agua (Bolados, 2016; Bolados et al., 2017; Roose and Panez, 2020). En Petorca, la calidad de vida de la población se ha visto afectada, muchos pozos no pueden proporcionar suficiente agua para satisfacer la demanda, y la producción de cultivos de algunos pequeños agricultores ha disminuido debido a la falta de agua para riego (Bolados et al., 2017; Panez-Pinto et al., 2018, 2017; Roose and Panez, 2020). Varios son los conflictos ocasionados por esta razón, algunos por la sequía y cambio climático, pero otros por la usurpación y el robo del agua, condicionado por las prácticas del agronegocio, resultado del modelo de gestión privada del agua (Bolados et al., 2017; Pinto, 2017). Por tanto, se escogen las cuencas La Ligua y Petorca para realizar esta investigación.

Algunas investigaciones realizan análisis socio-ecológicos sobre las desigualdades en el acceso humano al agua y la agroindustria, pero la relación entre la agricultura y la disminución actual de las GW, con respecto a otras posibles causas climáticas, está aún por aclarar, así como la relación de este agotamiento con los ecosistemas que sustentan.

De todo lo planteado surgen las siguientes preguntas científicas: ¿Estará relacionado el agotamiento de las GW con los cambios en la agricultura de las cuencas La Ligua y Petorca? ¿Los ecosistemas dependientes de las GW se han visto afectados por el agotamiento de los acuíferos?

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[1] Término que involucra procesos hidrológicos, meteorológicos y las decisiones respecto al uso del agua (oferta y demanda). Las zonas de escasez hídrica se decretan por un máximo de seis meses no prorrogables, durante los cuales la autoridad tiene facultades especiales para distribuir las aguas y aprobar nuevas extracciones. Los decretos de escasez se dictan con el objeto de proveer determinadas herramientas a usuarios del agua y a la población en general para reducir al mínimo los daños derivados de la sequía (DGA-MOP, 2019).

[2] La declaración de área de restricción de aguas subterráneas es un instrumento utilizado por la Dirección General de Aguas para proteger Sectores Hidrogeológicos de Aprovechamiento Común (SHAC) donde exista grave riesgo de descenso en los niveles de agua con el consiguiente perjuicio a los derechos de terceros establecidos en él, o bien, cuando los informes técnicos emitidos por el Servicio demuestren que está en peligro la sustentabilidad del acuífero (https://dga.mop.gob.cl).

Para tratar de resolver estas interrogantes se plantean las siguientes hipótesis:

I.5 Hipótesis y Objetivos

I.5.1 Hipótesis

H1: Los cambios en la agricultura han contribuido significativamente con el agotamiento de las aguas subterráneas en las cuencas La Ligua y Petorca en la última década.

H2: Los ecosistemas dependientes de las aguas subterráneas en las cuencas La Ligua y Petorca, se han visto afectados por el cambio de almacenamiento de los acuíferos en los últimos años.

Para evaluar las hipótesis se plantean los siguientes objetivos:

I.5.2 Objetivo general

Evaluar la relación entre los cambios en la agricultura y los ecosistemas dependientes con el agotamiento de las aguas subterráneas en las cuencas La Ligua y Petorca.

I.5.3 Objetivos específicos

OE1. Analizar la relación entre la agricultura con el agotamiento de las aguas subterráneas de las cuencas Ligua y Petorca (Publicación 1).

OE2. Analizar los cambios de los ecosistemas dependientes de las aguas subterráneas de las cuencas Ligua y Petorca ante el agotamiento de los acuíferos (Publicación 2).

CAPÍTULO II. MATERIALES Y MÉTODOS

En la presente sección se presenta un resumen de los principales materiales y métodos empleados en este estudio. Primero se realiza una caracterización físico-geográfica y socio-económica del área de estudio: las cuencas hidrográficas La Ligua y Petorca. Luego se presentan los datos principales empleados y sus fuentes respectivas. Por último, se exponen los métodos generales, que incluye el procesamiento de datos e imágenes satelitales, el cálculo de índices climáticos, topográficos y multiespectrales, procesamiento de encuestas, reclasificación y normalización de parámetros geoespaciales, evaluación multicriterio, análisis estadísticos y análisis espacio-temporales.

II.1 Área de Estudio

Las cuencas La Ligua y Petorca se localizan en el extremo norte de la región de Valparaíso (Centro-Norte de Chile), aproximadamente entre los 32º03'-32º38'S y los 70º27'-71º31'W (Figura 2.1a, b). Los ríos Petorca y La Ligua nacen en la precordillera andina, corren 106 km y 76 km, respectivamente y confluyen en el humedal costero Salinas de Pullally (Panez-Pinto et al., 2017). Las áreas de estas cuencas son de 1 986 km^2 y 1 980 km^2, sumando un total de 3 966 km^2. Por sus características de similar orientación, hidrogeología y área son consideradas gemelas. Presentan secuencias de unidades geológicas orientadas en el sentido norte-sur, formadas por rocas sedimentarias y volcánicas del Triásico al Pleistoceno, atravesadas por los cauces superficiales (Celedón, 2019; CNR and UDEC, 2016). En cada uno de los valles existe un acuífero no confinado y la ocurrencia principal de GW es alrededor de los canales principales en los valles precordilleranos, donde hay un relleno permeable formado por sedimentos granulares, que van desde cantos rodados hasta arenas finas. Según el estudio de Ayala et al. 2014 y reafirmado por un informe oficial de la Dirección de Aguas de Chile (DGA) (DGA-MOP, 2014) existen 12 sectores hidrogeológicos de uso común de GW (Figura 2.1c. En términos climáticos, la mayor parte del área presenta escasa humedad, cielos despejados, fuerte oscilación térmica diaria, y temperaturas medias anuales de 14.6°C (CNR and UDEC, 2016). Así entonces, estas cuencas se caracterizan por un clima semiárido con influencia mediterránea, un régimen predominantemente pluvial y sin glaciares en su sección de montaña andina (Panez-Pinto et al., 2017). Las precipitaciones varían entre 253 y 319 mm anuales, aumentando hacia la parte alta y concentradas en el invierno austral (Junio, Julio y Agosto) (Panez-Pinto et al., 2018, 2017).

Ambas cuencas se caracterizan una producción agrícola de índole frutícola (Muñoz et al., 2020; Panez-Pinto et al., 2018), dominada por cítricos y paltos, cuya expansión agrícola comenzó en la década de 1990 (Bolados et al., 2017; Roose and Panez, 2020). Otros cultivos presentes en la zona son los nogales, clementinas, almendros y naranjos (INDH, 2014; Panez-Pinto et al., 2018). La población actual se estima en más de 78 000 habitantes, la que se distribuye en mayor proporción en las comunas de La Ligua y se concentra principalmente en las áreas urbanas (67.3%) (INE, 2017).

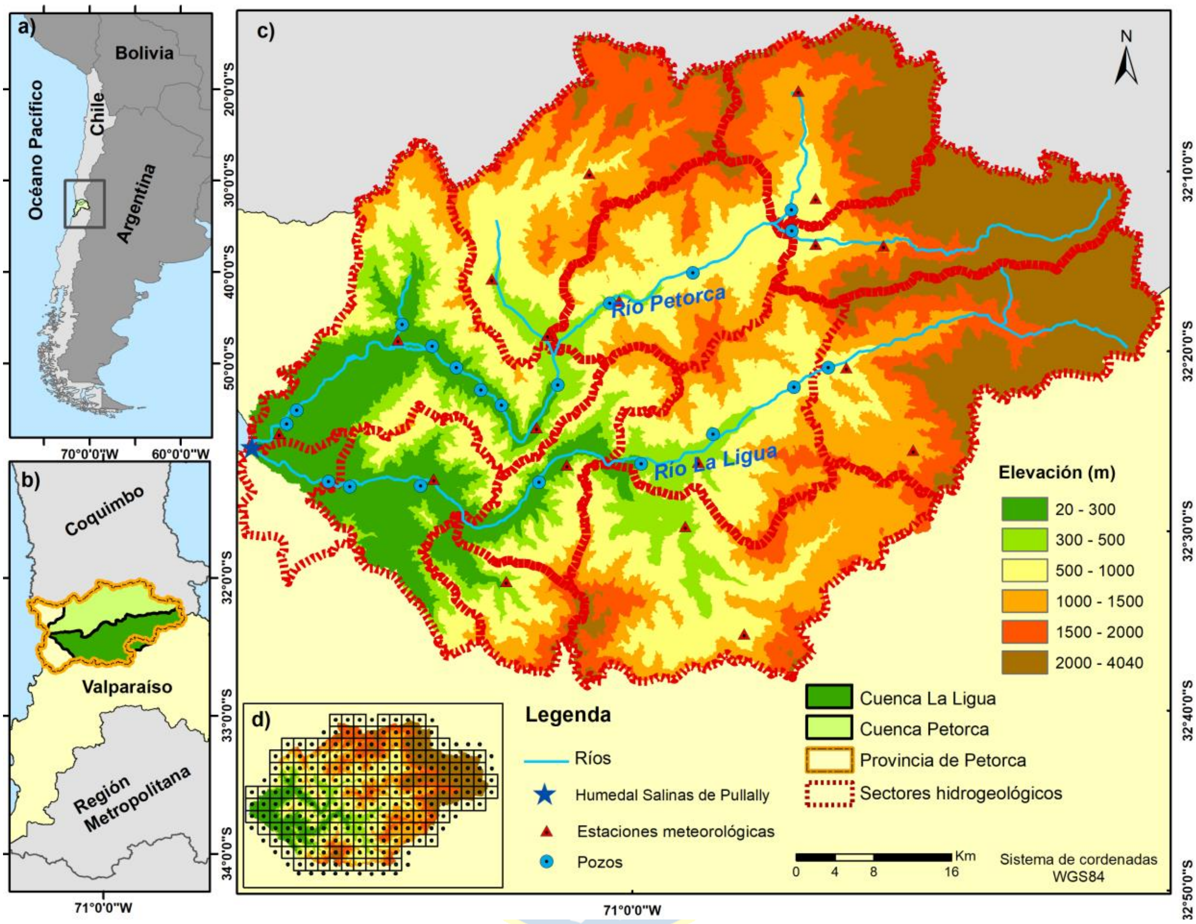

Figura 2.1. Ubicación del área de estudio. (a) entorno geográfico en América del Sur, (b) entorno geográfico en el Centro-Norte de Chile, región de Valparaíso y provincia de Petorca, (c) elevación, humedal Salinas de Pullally, ríos, sectores hidrogeológicos, estaciones meteorológicas y pozos, y (d) puntos grillados de datos del CR2MET.

II.2 Datos

En esta investigación se emplearon datos del nivel de GW de 20 pozos de observación obtenidos del sitio oficial de la Dirección General del Agua (Figura 2.1). Se seleccionaron de acuerdo con la calidad y calidad de datos, rango temporal y características hidrogeológicas, constituyendo un período de 16 años (2002-2017). La precipitación mensual se obtuvo de 20 estaciones meteorológicas del sitio web del Centro del Clima y la Resiliencia (CR)[2]. Además, se empleó la precipitación y la temperatura máxima y mínima del producto satelital CR2MET (Tabla 2.1).

El producto MODIS / 006 / MOD13Q1 (versión 6) del Centro de Archivo Activo y Distribuido de Procesos Terrestres (LP DAAC por sus siglas en inglés) del Servicio

Geológico de los Estados Unidos (USGS) se utilizó para obtener datos de series de tiempo NDVI (Índice de Vegetación de Diferencia Normalizada) del satélite MODIS (Espectrorradiómetro de Imágenes de Resolución Moderada). Las imágenes de este producto tienen una resolución espacial y temporal de 250 m y 16 días, respectivamente (Didan, 2015; Dong et al., 2017). Para obtener la clasificación del uso del suelo y varios índices de teledetección empleados en este estudio se procesaron imágenes del satélite Landsat. Las escenas que cubrían el área de estudio fueron 233/82 y 233/83 con una resolución espacial de 30 m.

El derecho de GW se refiere al derecho que se les confiere a los diferentes usuarios de utilizar este recurso, el cual se otorga a perpetuidad y sin costo (Buzolic et al., 2021). La legislación chilena actual (Código de Aguas de 1981) establece que el agua es un bien nacional de uso público y que se otorga a las personas el derecho a utilizarla (Muñoz et al., 2020). Los datos de derechos de GW utilizados fueron registrados por la DGA y se otorgan por cantidad y caudal medio anual de GW (Bolados et al., 2017; DGA-MOP, 2008).

La geología se adquirió del Servicio Nacional de Geología y Minería (SERNAGEOMIN) a una escala 1:1000000. Por último, el Modelo Digital de Elevación fue procesado a partir de 6 imágenes del satélite ALOS-PASAR del centro Alaska Satellite Facility (ASF). Todas las fuentes de datos y sus páginas web se detallan en la Tabla 2.1.

Tabla 2.1. Datos empleados y fuentes respectivas.

Datos	**Producto**	**Fuente**	**Fuente de ubicación**
GW	Pozos de observación	DGA	https://snia.mop.gob.cl/BNAConsultas/reportes
Precipitación	Estaciones meteorológicas	CR^2	https://www.cr2.cl/datos-de-precipitacion/
Precipitación	CR2MET	CR^2	https://www.cr2.cl/datos-productos-grillados/
Temperatura máxima y mínima	CR2MET	CR^2	https://www.cr2.cl/datos-productos-grillados/
Imágenes MODIS	MODIS/006/MOD13Q1	LP DAAC	http://lpdaac.usgs.gov
Imágenes Landsat	Landsat 5 TM, 7 ETM+ y 8 OLI	USGS	https://landsatlook.usgs.gov

Datos	Producto	Fuente	Fuente de ubicación
Derechos de GW	Derechos de aprovechamiento de aguas	DGA	https://dga.mop.gob.cl/productosyservicios
Geología	Capa temática Geología	SERNAGEOMIN	https://www.sernageomin.cl/
DEM	ALOS PALSAR	ASF	https://search.asf.alaska.edu/#/

II.3 Métodos

La relación entre el agotamiento de las GW y el desarrollo de la actividad agrícola fue evaluada a través de un enfoque interdisciplinario que integró variables hidro-climáticas, productos satelitales y datos de derechos de GW. Los datos del nivel de las GW en el período 2002-2017 se procesaron a escala mensual y anual. Luego estos valores anuales fueron estandarizados. El Índice Estandarizado de Precipitación (SPI) a escalas temporales de 1, 3, 6, 9,12 y 24 meses se empleó para relacionar la sequía con las GW. Este índice se calculó con los valores mensuales de la precipitación obtenida tanto de las estaciones meteorológicas, como del producto satelital CR2MET (1979-2016), usando el paquete SPEI en el software R Student. Una serie de tiempo MODIS-NDVI fue procesada en la plataforma Google Earth Engine (GEE) desde el 2002 hasta el 2017. GEE es una plataforma de programación en la nube que ofrece Google para el análisis rápido de información satelital (Gorelick et al., 2017; Zheng et al., 2019). Luego se procesaron 5 imágenes Landsat (TM, ETM+ y OLI) que fueron empleadas para obtener una clasificación del uso del suelo mediante una clasificación supervisada con el clasificador Random Forest en GEE. Los derechos de las GW se analizaron a nivel de comuna y de manera mensual y anual, tanto en cantidad de derechos como en caudal promedio. Todos los datos empleados fueron analizados estadísticamente mediante correlaciones, correlaciones cruzadas, pruebas de tendencia y puntos de cambios (Test de Mann Kendall, Pendiente de Sen y Estimador de punto de cambio de Pettitt) y análisis de conglomerados. Otros softwares empleados fueron XLSTAT 2019 v3.2, ENVI 5.3, TerrSet y ArcGIS 10.8.1.

Un nuevo método geoespacial con un enfoque integrado y temporal fue desarrollado para mapear Zonas Potenciales de Ecosistemas Dependientes de las Aguas Subterráneas (PGDEZ en inglés) con el objetivo de analizar los cambios espacio-temporales de los GDE ante el nivel cambiante de las GW. Se realizó una encuesta a expertos para asignar peso a distintos parámetros geoespaciales considerados como predictores de la presencia de GDE. Se empleó información geoespacial convencional (Geología, Geomorfología, Uso del Suelo y Lluvia), parámetros topográficos, índices multiespectrales y variables climáticas. Luego 14 parámetros geoespaciales fueron reclasificados y normalizados en una escala de 1 a 5 según la alta o baja probabilidad de encontrar un GDE (muy alta, alta, media, baja y muy baja). El mapeo se llevó a cabo mediante la herramienta de superposición ponderada en ArcGIS 10.8.1 y la validación se realizó mediante trabajo de campo. Por último, los cambios espacio-temporales de los GDE entre el 2002 y el 2017 fueron relacionados con las GW a través del NDVI de verano. Con este fin se analizaron estadísticamente datos de GW, lluvia y NDVI mediante una correlación y una regresión lineal.

La metodología general se muestra en el diagrama de la Figura 2.2. No obstante, las técnicas y métodos empleados en esta investigación doctoral se describen detalladamente en los capítulos respectivos.

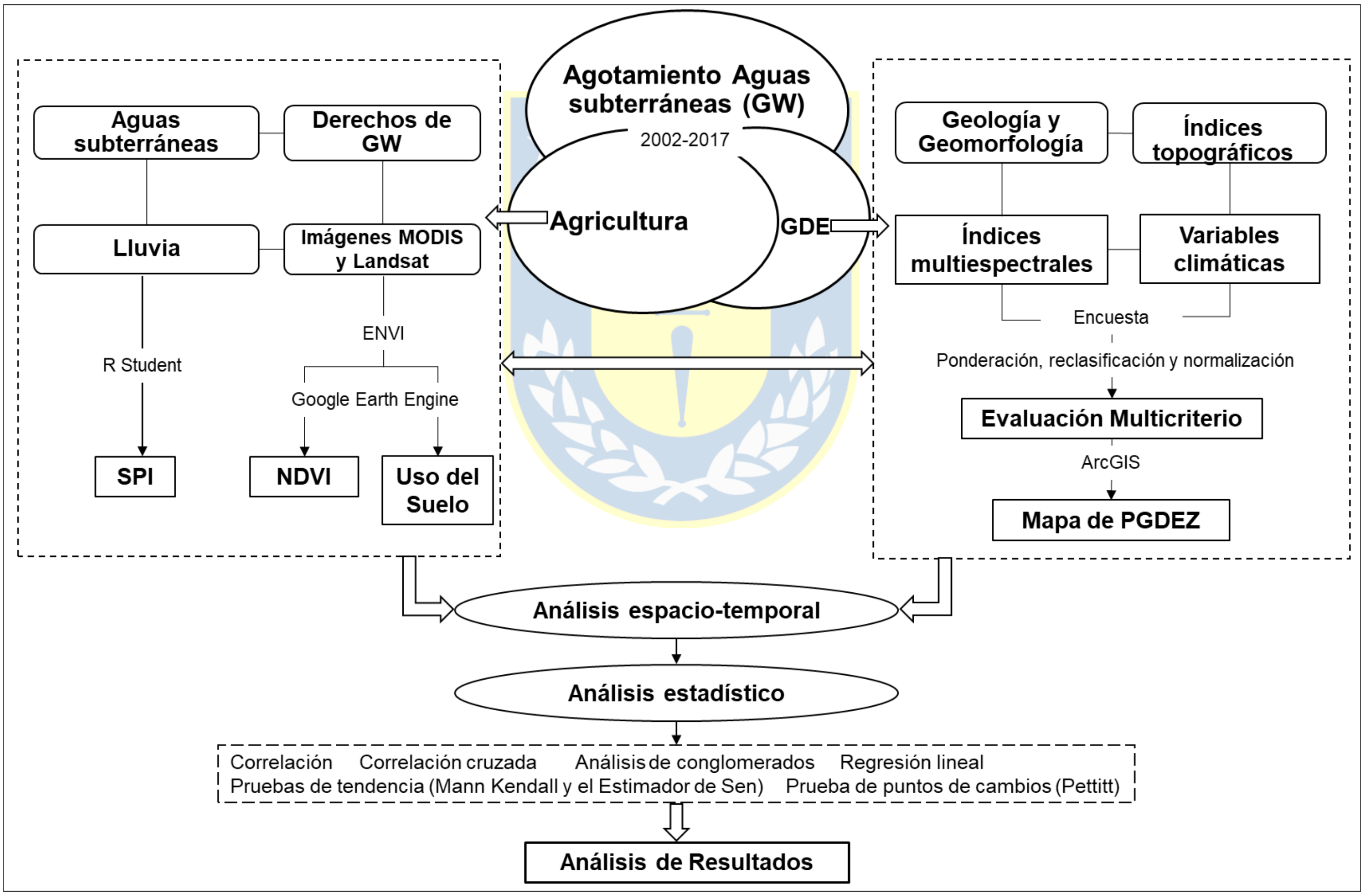

Figura 2.2. Esquema metodológico

CAPÍTULO III. AGOTAMIENTO DE LAS AGUAS SUBTERRÁNEAS Y AGRICULTURA EN LAS CUENCAS LA LIGUA Y PETORCA

En el presente capítulo se muestran los resultados publicados en un primer artículo científico en la revista ***Water*** de la base de datos **WoS**.

Duran-Llacer, I.; Munizaga, J.; Arumí, J.L.; Ruybal, C.; Aguayo, M.; Sáez, K.; Arriagada, L.; Rojas, O. Groundwater Depletion in Chile´s Ligua and Petorca Watersheds through an Interdisciplinary Approach. *Water* 2020, Volume 12, Issue 9, 2446. https://doi.org/10.3390/w12092446.

III.1 Resumen

El agua subterránea (GW) es la principal fuente de agua dulce no congelada del planeta y, en muchas áreas semiáridas, es la única fuente de agua disponible durante los períodos de estiaje. En el centro-norte de Chile, se ha producido un agotamiento de GW como resultado de condiciones semiáridas y alta demanda de agua, lo que ha desencadenado importantes conflictos sociales, algunos por la sequía y otros por el agronegocio en el contexto de un modelo privado de gestión del agua. Se estudiaron las cuencas La Ligua y Petorca en la Región de Valparaíso con el fin de analizar la influencia de factores climáticos y antrópicos en el agotamiento de las GW. Se utilizó un enfoque interdisciplinario que integra variables hidroclimáticas, técnicas de datos de teledetección y datos de derechos de GW, lo que promueve el manejo sostenible de las GW. Se calculó el Índice Estandarizado de Precipitación (SPI) y el Índice de Vegetación de Diferencia Normalizada (NDVI), y se analizó el cambio del uso del suelo entre 2002-2017. Se demostró que el GW disminuyó significativamente (en el 75% de los pozos) y que la sequía hidrológica fue moderada y prolongada (sequía más larga de los últimos 36 años). El área de cultivo del palto en la Ligua aumentó significativamente (2 623 ha) con respecto a otras áreas agrícolas (mayor disminución del GW), mientras que en Petorca disminuyó en 128 ha. Además, las correlaciones GW-lluvia fueron bajas y los derechos GW se otorgaron continuamente a pesar de la sequía. Los resultados confirmaron que el agotamiento de los acuíferos fue influenciado principalmente por factores humanos debido a la sobreexplotación por la agricultura y la falta de gestión del agua.

Palabras claves: aguas subterráneas; sequía; NDVI; cambio del uso del suelo; agricultura; derechos de aguas subterráneas; gestión de los recursos hídricos subterráneos water

MDPI

Article

III.2 Lessons to Be Learned: Groundwater Depletion in Chile's Ligua and Petorca Watersheds through an Interdisciplinary Approach

Iongel Duran-Llacer 1, * , Juan Munizaga 1, José Luis Arumí 2 , Christopher Ruybal 3 , Mauricio Aguayo 1, Katia Sáez-Carrillo 4, Loretto Arriagada 1 and Octavio Rojas 1

[1] Faculty of Environmental Sciences and EULA-Chile Center, Department of Territorial Planning, University of Concepcion, Víctor Lamas 1290, Concepción 4070386, Chile; juanmunizaga@udec.cl (J.M.); maaguayo@udec.cl (M.A.); nancyarriagada@udec.cl (L.A.); ocrojas@udec.cl (O.R.)

[2] Department of Water Resources, CHRIAM Water Center, University of Concepcion, Vicente Mendez 595, Chillán 3812120, Chile; jarumi@udec.cl

[3] U.S. Fulbright Program-Chile, Department of Water Resources, University of Concepcion, Chillán 3812120, Chile; cruybal@mymail.mines.edu

[4] Department of Statistics, Faculty of Physical and Mathematical Sciences, University of Concepcion, Víctor Lamas 1290, Concepción 4070386, Chile; ksaez@udec.cl

* Correspondence: ioduran@udec.cl or iongel.duran@gmail.com

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Abstract: Groundwater (GW) is the primary source of unfrozen freshwater on the planet and in many semi-arid areas, it is the only source of water available during low-water periods. In north-central Chile, there has been GW depletion as a result of semi-arid conditions and high water demand, which has unleashed major social conflicts, some due to drought and others due to agribusiness practices against the backdrop of a private water management model. The Ligua and Petorca watersheds in the Valparaíso Region were studied in order to analyze the influence of climatic and anthropogenic factors on aquifer depletion using an interdisciplinary approach that integrates hydroclimatic variables, remote sensing data techniques, and GW rights data to promote sustainable GW management. The Standardized Precipitation Index (SPI) and Normalized Difference Vegetation Index (NDVI) were calculated and the 2002–2017 land-use change was analyzed. It was shown that GW decreased significantly (in 75% of the wells) and that the hydrological drought was moderate and prolonged (longest drought in the last 36 years). The avocado-growing area in Ligua increased significantly—by 2623 ha—with respect to other agricultural areas (higher GW decrease), while in Petorca, it decreased by 128 ha. In addition, GW-rainfall correlations were low and GW rights were granted continuously despite the drought. The results confirmed that aquifer depletion was mostly influenced by human factors due to overexploitation by agriculture and a lack of water management.

***Keywords**:* groundwater depletion; drought; NDVI time series; land-use change; agriculture; groundwater rights; groundwater resources management

1. Introduction

Groundwater (GW) is a very valuable resource as it accounts for 96% of the planet's unfrozen freshwater [1]. As a part of the hydrological cycle, GW is an essential source of water for human use and agricultural and industrial activities [2], as well as the main source of water in arid and semi-arid regions [3,4]. It is estimated to supply 36% of drinking water, 42% of irrigation water, and 24% of industrial water worldwide [1].

GW use has increased significantly in recent decades and storage has decreased, with over 20% of aquifers estimated to be overexploited due to a lack of sustainable GW management [1]. This has had various impacts such as water scarcity, land subsidence, saline intrusion, and reduction of baseflow to rivers, lakes, and wetlands [1,5]. The storage decrease may be a consequence of global climate change, which affects hydrological patterns, water levels, and rainfall patterns; however, agricultural irrigation, land-use change, and reservoir construction can also have repercussions [2,6].

Drought is manifested in the hydrological system on different time scales and contributes to the decrease in aquifer storage as it affects recharge and water levels, such that it can also affect agricultural activity [2]. It can be subdivided into meteorological, agricultural, hydrological, and socioeconomic drought [6–8]. Meteorological drought occurs due to a decrease in rainfall below the average and if it continues for several months, it becomes agricultural drought as it decreases the amount of water available for soil and crops [6,8]. Hydrological drought is characterized by scarcity of surface and GW sources [7,9], while socioeconomic drought occurs when water scarcity affects the supply and demand of economic goods [8,10].

In addition to drought, accelerated land-use change (agricultural and urban expansion) has also generated a decrease in GW recharge and storage [11,12], mainly in semi-arid regions [11]. Such negative effects must be monitored and mitigated to guarantee sustainability [11]. Aquifer depletion can be mitigated through sustainable GW management as it is a fundamental tool capable of achieving an equilibrium between water availability and extraction, ensuring its protection and efficient use for current and future generations [1,13].

The water management model in Chile is among the most privatized and commoditized in the world [14,15]. This water allocation system is regulated by a use rights market, in which rights are granted by the state to private users in perpetuity and at no cost. In addition, each owner can exchange their rights at market prices; thus, public regulation and supervision mechanisms are quite limited [16]. This has resulted in increasing inequality regarding water access and social conflicts over water resources gaining political attention [15,17].

Of the 88 m3/s of GW extracted throughout Chile, 49% is used in agriculture [18] and many intensive agricultural activities, mainly in north-central Chile, are based on the use of underground sources due to the semi-arid conditions of the region [19]. In fact, many watersheds in this area, including the Ligua and Petorca watersheds in the Valparaíso Region, present a high degree of exploitation that in some cases has exceeded aquifer sustainability levels [19,20]. The Petorca Province, located in this area, was declared a water scarcity zone in 1997 [16,21] and a GW restriction zone in 2014 [21]. In Petorca, the quality of life of the population has been affected, many wells are unable to provide enough water to meet demand, and the crop production of some small farmers has decreased due to the lack of water for irrigation [14,15,17,22,23]. This has led to various social conflicts, some due to drought or climate change and others to water theft by large growers, a result of the private water management model [14,17,24].

Some investigations have focused on socioecological analyses of inequalities in human access to water and agribusiness amid the water crisis in Petorca [14,17,22,23,25] and a few have analyzed hydroclimatology in this context [16,19,20]; however, it is necessary to carry out studies with interdisciplinary approaches that analyze the causes of GW decreases in these watersheds and can be applied in other analogous investigations worldwide. Therefore, the purpose of this study was to analyze the influence of climatic and human factors on aquifer depletion in the Ligua and Petorca watersheds through an interdisciplinary approach using hydroclimatic variables, techniques for processing satellite remote sensing data, and GW rights data that promote sustainable GW resources management in agricultural and semiarid zones. This study integrates approaches of different methodologies, concepts, techniques, and evaluation schemes from a variety of disciplines to investigate the environmental problem of aquifer depletion. Figure 3.1 depicts the environmental problem in the study area.

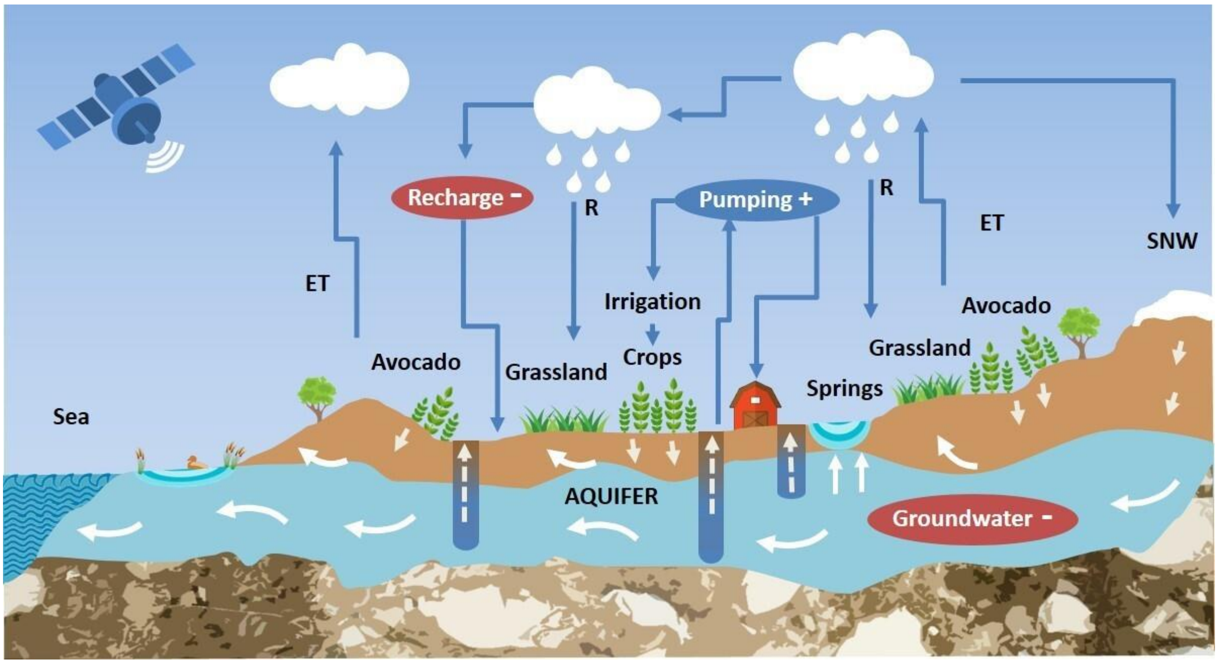

Figure 3.1. Conceptual diagram of the relationship among groundwater (GW), agriculture, and rainfall in the study area. ET—evapotranspiration, R—rainfall, and SNW—snow.

2. Materials and Methods

2.1 Study Area

The Ligua and Petorca river watersheds (32° S, 1980 km2 and 1986 km^2, respectively) are located in the Valparaíso Region (north-central Chile) (Figure 3.2b,c). The two rivers meet at the Salinas de Pullally coastal wetland and their watersheds have similar physical-geographical characteristics [17,20,26]. They are characterized by semi-arid conditions; a predominantly pluvial (pluvio-nival), mixed regime; and an absence of glaciers in their Andean sections, which makes them vulnerable in terms of water availability [16,17,23]. Annual rainfall varies between 253 and 319 mm, increasing in the upper parts and concentrated in the austral winter (April–October) [17,22,26]. The primary occurrence of GW is around the main channels in pre-cordillera valleys, where there is permeable fill made up of granular sediment, ranging from boulders to fine sand. In each of the valleys, there is an unconfined aquifer, both of which are highly permeable, resulting in a high degree of interaction between surface water and GW [17,26]. According to the study of Ayala et al. [19] and reaffirmed by an official report of the Chilean Water Directorate (DGA, for its initials in Spanish) [27], there are 12 hydrogeological sectors of common GW use (Figure 3.2c).

Both watersheds are characterized by agricultural fruit production [14,16,17,22,24], dominated by citrus and avocado, the agricultural expansion of which began in the

1990s [14,22,23].

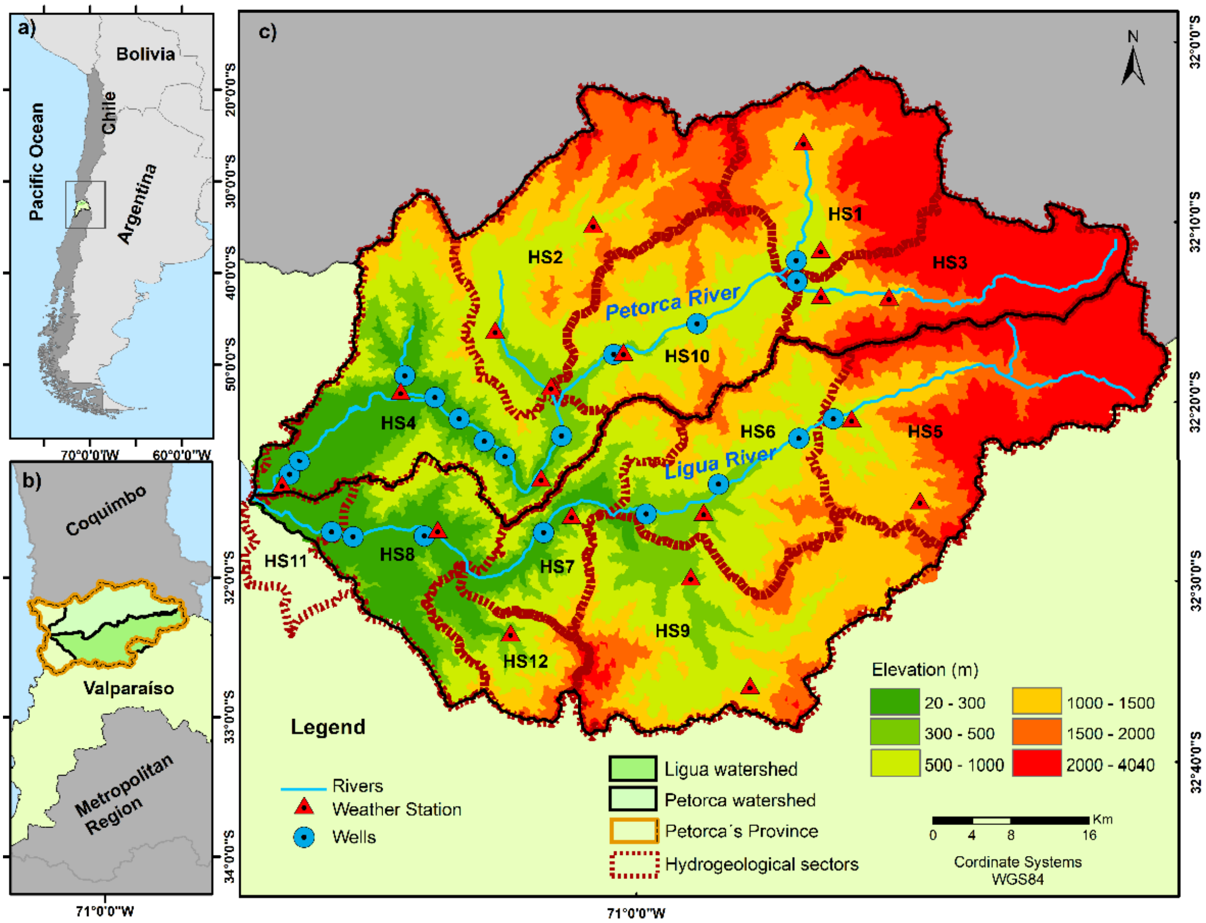

Figure 3.2. Location of the Ligua and Petorca watersheds; (a) shows the geographic setting in South America, (b) the geographic setting in Chile and the Petorca Province, and (c) wells, weather stations, hydrogeological sectors (HS), and elevation.

2.2 Data Acquisition

2.2.1 GW and Rainfall Data

The 20 observation wells were obtained from the official site of the DGA, https://dga.mop. gob.cl/Paginas/default.aspx; those with the best data quality, temporal range, and hydrogeological characteristics were selected, constituting a period of 16 years (2002–2017) (Figure 3.2c). The rainfall data of the 1980–2017 period was acquired from the Center for Climate and Resilience Research (CR2) and are available at http://www.cr2.cl/. Twenty weather stations were used and the gridded monthly rainfall dataset CR2MET was also obtained from the same web site. CR2MET is a spatially distributed dataset developed for Chile that is currently being used by the DGA to update the national water balance; it has a resolution of 0.05◦ and is available from 1976 to 2016 [28]. This gridded dataset is based on networks of land stations with the most complete data, a statistical downscaling of ERA-Interim reanalysis data and local topography [28,29].

2.2.2 Satellite Data

The MODIS/006/MOD13Q1 product (version 6) of the Land Processes Distributed Active Archive Center (LP DAAC, http://lpdaac.usgs.gov) was used to obtain MODIS (Moderate Resolution Imaging Spectroradiometer) NDVI time series data. The Terra images of this product have a spatial and temporal resolution of 250 m and 16 days, respectively [30,31]. To generate the cover and land-use results, Landsat images with a spatial resolution of 30 m from 2002 and 2017 were used (Table 3.1), which are available on the official site of the United States Geological Survey (USGS) https://landsatlook.usgs.gov/.

Table 3.1. Description of images for classification.

Date	Path and Row	Sector	Sensor Type
21 March 2002	233 82	Northern, headwaters, and middle sectors of the watersheds	Landsat 7 ETM+
21 March 2002	233 83	Southern, headwaters, and middle sectors of the watersheds	Landsat 7 ETM+
20 March 2002	01 82	Western and lower sectors of the watersheds	Landsat 5 TM
1 January 2017	233 82	Northern, headwaters, middle, and lower sectors of the watersheds	Landsat 8 OLI
1 January 2017	233 83	Southern, headwaters, middle, and lower sectors of the watersheds	Landsat 8 OLI

2.2.3 GW Rights

Water rights are granted to private users in perpetuity and at no cost. Current Chilean legislation (1981 Water Code) establishes that water is a national asset for public use and that individuals are granted the right to use it. This right of use is a real right and consists of the use and enjoyment of water [15,16]. There are two types of rights registered: surface and GW rights [32]. The GW rights data used were recorded by the DGA, which, according to Article 122 of the Water Code, collects information on original rights and requests associated with groundwater. Rights are granted to users, in accord with established regulations, for a given use and are granted by GW quantity and annual average streamflow [14,32]. In the DGA's Manual of Regulations and Procedures for Water Resources Administration [32], the nomenclature of each type of right is established, as shown below.

Use rights (ND, for the abbreviation in Spanish) are new rights that are granted in wells, pumping stations, culverts, or driven point wells. Intake point changes (VPC, for the abbreviation in Spanish) are rights that are authorized by the DGA to be transferred from an intake point within a hydrogeological sector. Right regularization (NR, for the abbreviation in Spanish) is requested by a user and consists of registration of a right in his or her name, be it an unregistered right or one that belongs to someone else, while old users (UA, for the abbreviation in Spanish) are those who have had GW rights for many years, be it through a water grant or a transaction [32].

2.3 Methods

This section presents the data processing steps, the analysis methods employed, and their integration through an interdisciplinary approach. The spatial-temporal and statistical analysis are carried out between watersheds and by the hydrogeological sector. Additionally, satellite image processing, drought and vegetation index calculation, land-use modeling using new programming technology, trend test statistical analysis, and general statistical analysis are described below. The general diagram is shown in Figure 3.3.

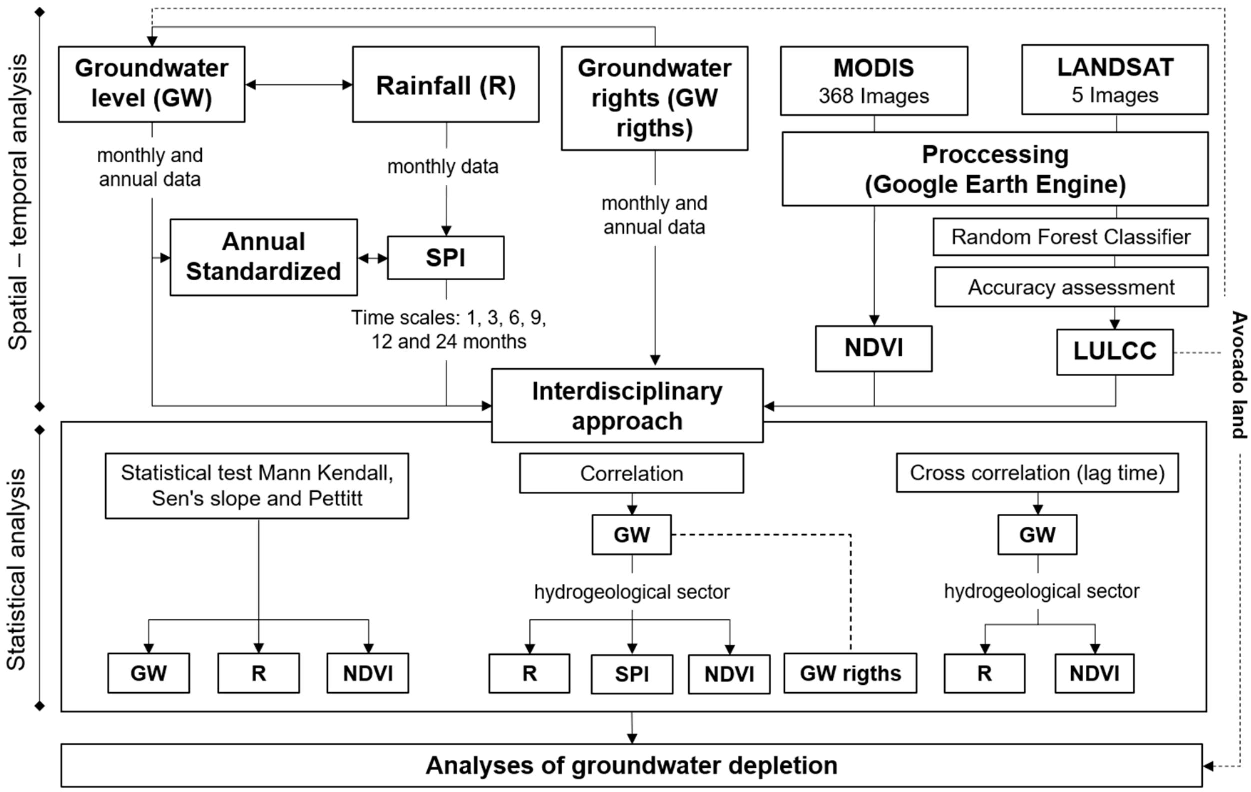

Figure 3.3. General methodology diagram

2.3.1 GW, Rainfall, and GW Rights Processing

The GW values of each well from the 2002–2017 period, were analyzed on a monthly and annual basis, as were the in situ rainfall data. The annual GW averages were obtained by watershed and wells and represented on a map. In addition, the annual GW values were standardized in accordance with Hu et al. [33]. The standardization, Z, is carried out by subtracting the long-term mean value of the distribution from the annual value and dividing the result by the standard deviation, as shown in the following equation:

$$Z = (X - \mu)/\sigma, \quad (1)$$

where X is the value that is being standardized, μ the mean of the distribution, and σ the standard deviation of the distribution.

The gridded rainfall data were processed and correlated with the in situ data to evaluate the representativeness of this source. The results presented Pearson coefficients between 0.98 and 0.99 (p-value < 0.0001) at all the weather stations. The statistical analyses were carried out in XLSTAT 2019 v3.2 (Addinsoft, Paris, France).

The granted GW rights were processed at a commune or municipality level within the studied watersheds, with only those in the area selected. The data were processed at monthly and annual levels, in terms of both quantity of rights and average streamflow, resulting in a time series, and then new rights were correlated with GW levels (Table 3.1).

2.3.2 Drought Index

The Standardized Precipitation Index (SPI) [34] is an index that is widely used to identify droughts and wet events based on temporal rainfall data [35–37]. It is among the most used indices worldwide for drought monitoring and the World Meteorological Organization (WMO) considers it the universal drought index [35]. It is calculated by taking the difference between precipitation and the mean of a given time period and then dividing it by the standard deviation [36], as shown in Equation (2). Subsequently, it is fit to a gamma distribution and is transformed into a normal distribution [36–38].

$$SPI = (X_i - X_j)/\sigma, \quad (2)$$

where Xi is monthly rainfall, Xj the mean value of the time period, and σ the standard deviation.

The SPI has been used to establish relationships between drought and GW levels in some research [2,6,9,35,36]. This affirmation is based on the fact that a rainfall deficit could lead to a lack of GW recharge [2,6]. Therefore, the SPI between 1982 and 2017 was calculated at 19 weather stations and 191 grid points of the CR2MET dataset at different time scales (1, 3, 6, 9, 12, and 24 months) using the SPEI package in R Student software. The advantage of these time scales is their use, in the case of three months or less, in drought monitoring tasks; in the case of six months or less, in monitoring effects on agriculture; and, in the case of 9 months or more, in monitoring hydrological effects [39].

SPI 12 and 24 from 2002 to 2016 in various seasons of the year in Chile—summer (December, January, February), autumn, (March, April, May), winter (June, July, August), and spring (September, October, November) [40]—were represented spatially using the ordinary Kriging interpolation method in ArcGis 10.7.1, as it presented lower semivariogram errors compared to other methods. This method has proven to be superior to others and has been used in other investigations to interpolate rainfall, the SPI, and even GW [33,41,42]. Then, the annual SPI values were calculated to analyze them with the annual standardized GW values.

To facilitate the discrimination of drought and non-drought conditions, the classification used by [43] was employed, where values ≥2 represent extremely wet, 1.5 to 2 severely wet, 1 to 1.5 moderately wet, 1 to 0.5 mildly wet, 0.5 to −0.5 normal, −0.5 to −1 mild drought, −1 to −1.5 moderate drought, −1.5 to −2 severe drought, and ≤−2 extreme drought.

2.3.3 Normalized Difference Vegetation Index NDVI

The so-called spectral vegetation greenness indices derived from satellite data such as the NDVI are tools for monitoring vegetation conditions [44]. This index consists of the spectral reflectances of the normalized ratio of the near infrared and red bands [44] (see Equation (3)); it has been widely used in remote sensing of vegetation for decades [42]. It shows variations in sensitivity to global climate changes and sensitivity to precipitation; this sensitivity is particularly high in arid and semi-arid areas [42]. It is important to consider that studies with different data such as rainfall and NDVI, among others, provide key information on regional vegetation changes resulting from climatic and human factors [44].

$$NDVI = NIR - R/NIR + R, \tag{3}$$

where NIR is the near infrared band and R the red band.

The NDVI data were processed using the programming technology offered by Google Earth Engine (GEE). Google Engine is a cloud platform for rapid analysis using the information technology infrastructure of Google [42,45,46]. This NDVI was calculated based on atmospherically corrected bidirectional surface reflectances that have been masked for water, clouds, heavy aerosols, and cloud shadows [30]. A monthly time series from 2002 to 2017 throughout the study area was obtained after processing 368 images. Then, these values and the filtered NDVI were analyzed for the area below 800 m as this is the maximum elevation that avocado crops have reached (previously identified in Google Earth software and extracted through the Digital Elevation Model (DEM) in ArcGIS 3D analysis tools); therefore, it was used as an estimate of the total agricultural area.

2.3.4 Land Use/Land Cover Change LULCC

The composite preprocessing began with geometric correction (reprojection to UTM-WGS84 coordinate system, zone 19 S) [11]. Subsequently, a topographic correction was applied to eliminate the illumination effects of the relief by applying the normalization method described by Richter et al. [47].

Then, for the atmospheric correction (TOA), the methodologies of Chander et al. [48] and the USGS (https://www.usgs.gov/land-resources/nli/landsat/using-usgs-landsat-level-1-data-product) were followed. The TOA correction method consists of a transformation of the digital values (DN) of the pixels into reflectance values. Next, to obtain a better atmospheric correction, the Dark Object Subtraction technique was applied [49]. Both corrections were applied in ArcGIS, ENVI, and TerrSet software.

The land-use classification proposed in this study was based on the classification (or nomenclature) of Zhao et al. [50], which was modified according to the interests of the investigation (Table 3.2).

Table 3.2. Description of the land uses employed in the investigation.

Name	Description
Fruit land	Cultivation of fruit trees such as lemon, orange, and walnut, among others
Avocado land	Cultivation of mature and young avocado trees
Agricultural land	Traditional agriculture, dominated by vegetable plantations and prairie crop rotation
Bare soil	Soil with little or no vegetation. Includes rocky areas
Scrubland	Bush areas, generally dominated by sclerophyll arborescent shrubs
Native forest	Native forest, essentially sclerophyll
Exotic plantation	Forestry plantation, dominated by the species Eucalyptus and Pinus radiata
Water bodies	Natural water bodies such as rivers, estuaries, ponds, and lakes
Reservoirs	Water stored artificially in ponds and reservoirs
Urban	Urban land associated with the urban fabric, manufacturing, highways, and roads

To generate the classification, approximately 600 field monitoring points were used, which served as the basis for taking 150 points for each class (10 classifications), for a total of 1500 points. Based on these points and other new points generated using band combinations, 1500 points were also established for the 2002 classification. Subsequently, a non-parametric classifier called Random Forest (RF) [51–53] was selected to generate the classification using the GEE platform. RF is a classifier that uses multiple decision trees to classify pixels and then performs voting to give each pixel a final category. This classifier uses two hyperparameters: the number of trees and $\sqrt{n}$, where n is the number of bands. These hyperparameters were configured with 500 decision trees, in accordance with Zhang et al. [54].

To increase the discrimination and separability of the proposed classes, a series of additional bands was calculated and incorporated into the model. The bands generated to improve the classification of each image from 2002 and 2017 were: NDVI, NDWI (Normalized Difference Water Index), SAVI (Soil Adjusted Vegetation Index), MSAVI (Adjusted SAVI), NBR (Normalized Burn Ratio), DEM (Digital Elevation Model), and Slope. Once the classifications were carried out, the precision parameters of each image were calculated; to this end, the Kappa index and overall accuracy were calculated for each of the classifications.

2.3.5 Statistical Tests and Correlation

To analyze the trends of the monthly and annual GW levels, rainfall and NDVI data, non-parametric Mann Kendall tests [55,56], and Sen's slope [57] were used as they do not require normal distribution and homoscedasticity of data and present the advantage of accommodating missing measurements and atypical values in a time series [2,58]. The level of significance used in all the tests was a p-value < 0.05. The Pettitt test was used for the significant change points in the time series or abrupt changes [59]. Pettitt is another non-parametric test and has been widely used to detect change points in environmental and hydrological data [60]. When the p-value is less than 0.05, there is a significant change point and the series is divided into two parts [7].

The correlation and cross-correlation analyses were carried out by the hydrogeological sector (Figure 1.2c) and not at a pixel scale as vegetation or crops can be affected both in the vicinity of the extraction well and in a large area very distant from it, as the water is extracted from one site and used for irrigation in others. A Pearson correlation was applied to the average of GW, gridded rainfall, SPI (scales 1, 3, 6, 9, 12, and 24 months), and NDVI by the hydrogeological sector up to 800 m. The aim of this analysis was to investigate spatial and temporal relationships among GW and rainfall (effect of rainfall over GW recharge), drought, and vegetation (likely effect of irrigation). In addition, a cross correlation (time lag of 1 to 6 months) was made between GW-rainfall and GW-NDVI. Cumulative GW rights, both number of rights and annual average streamflow granted, were also correlated with GW levels.

The k-means non-hierarchical cluster used by Chu [9] was applied to the GW values of each well to establish similarities or differences between the behavior of each well and thus obtain groupings of wells with similar characteristics through statistical analyses and then to find links between aquifer depletion and anthropogenic factors.

3. Results

3.1 Temporal and Spatial Variation of GW and Rainfall

In Figure 3.4, a water level decrease is observed in the 2002–2016 period at all the analyzed wells, which is steeper at some wells in the Ligua watershed located in the south of the study area (Figure 3.4b). In general, a water level decrease and many wells with values below the average, mostly from 2009 and 2010 (75% respect to annual average), are observed (Figure 3.4a,b). The wells with the greatest decreases in the Petorca watershed are located in the upper eastern section (O. Chalaco and L. Silva), while the wells with the greatest aquifer decrease of both watersheds are in the central valley of the Ligua watershed (S. Lorenzo and Aconcagua), with decreases of over 10 and 15 m, respectively (Figure 3.5).

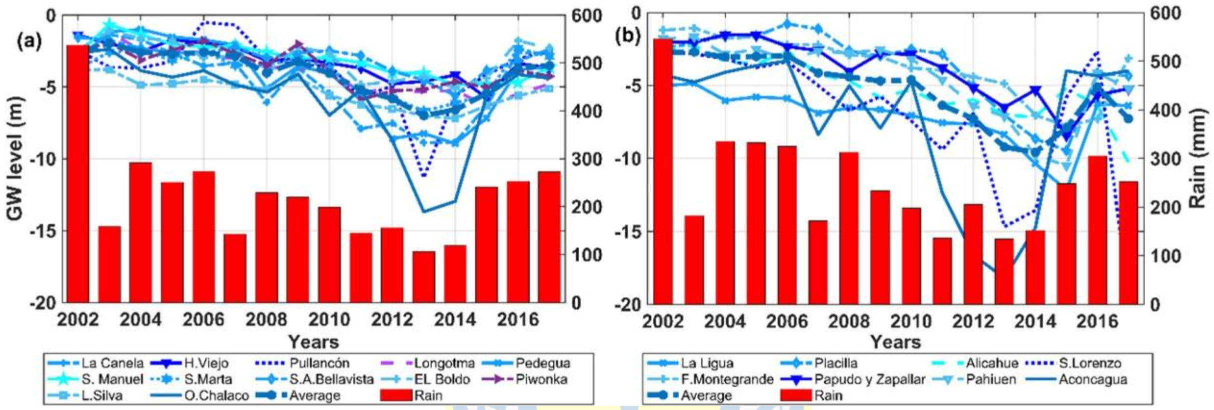

Figure 3. 4. Annual average GW level by well and watershed and annual average rainfall in (a) Petorca watershed and (b) Ligua watershed from 2002–2017.

Annual rainfall presented a decrease that exceeded 350 mm starting in 2003 (67.7% of the annual average), but, as with GW, the decrease was more critical from 2009 and 2010, as rainfall was below 200 mm for several years (Figure 3.4a,b). However, no differences in rainfall behavior between watersheds were observed, unlike with GW, as the decrease is homogenous throughout the area.

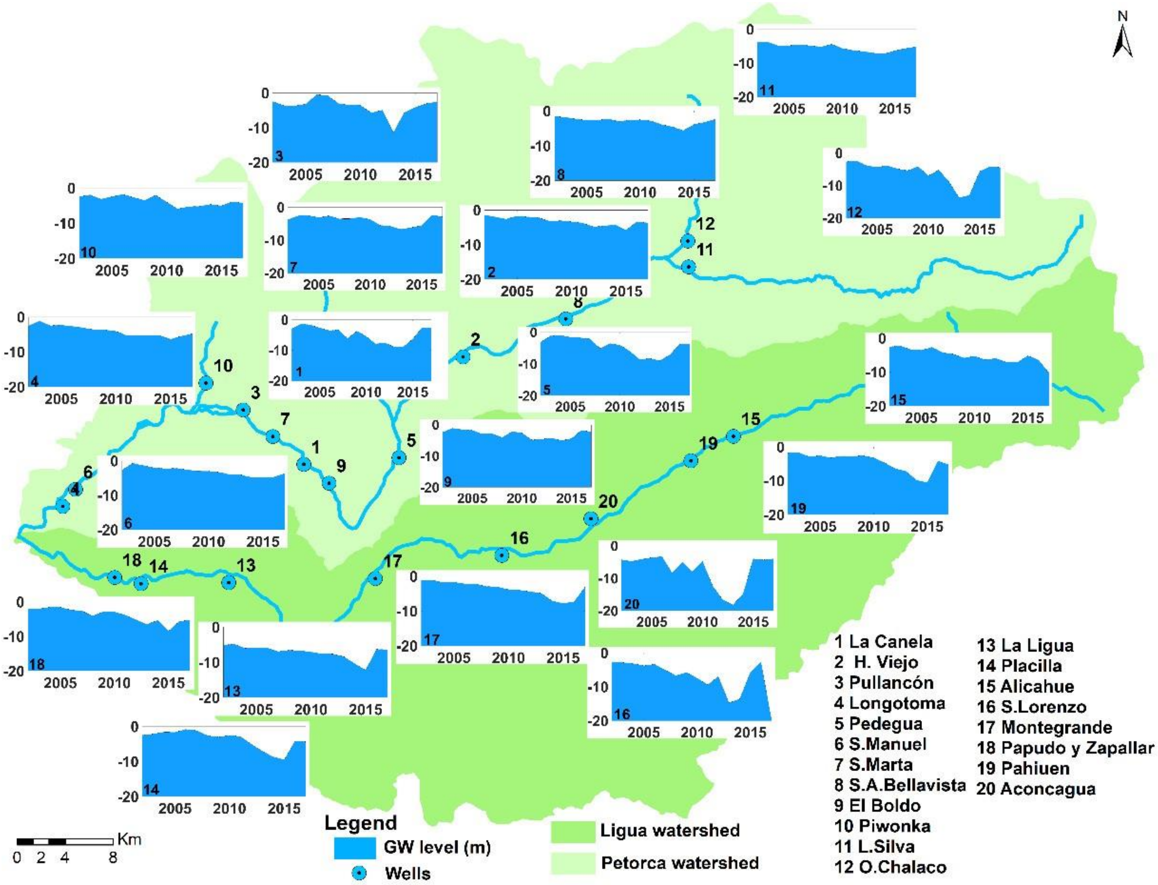

Figure 3.5. Spatial distribution of annual GW averages from 2002–2017 in the study area.

3.1.1 SPI-Based Drought Assessment

SPI 1 and 3 do not show drought conditions; only short intervals of wet (blue) and dry (red) conditions are observed. Starting with SPI 6, dry periods associated with an agricultural drought are observed (Figure 3.6c), while SPI 9, 12, and 24 show well-defined dry periods, mainly from 2010 to 2015, so this drought is defined as hydrological drought. The index values of those years are between −0.5 and −1.5, reaching −2 in months of 2014 and 2015; thus, the drought is classified as between weak and severe. The spatial distribution of SPI 12 and 24 (Figure 3.7) coincides with the time series observed in Figure 3.6e,f. From 2002 to 2004, a wet period is presented. Then, normal conditions are maintained through 2009, with the hydrological drought appearing, starting in 2010; however, this drought occurs in both watersheds with no spatial difference and is observed in every season of the year, although in autumn (MAM) and winter (JJA), it was slightly more intense.

In general, the SPI shows a moderate but very prolonged hydrological drought (2010–2015) that coincides with the previously identified period of greatest GW decrease, as well as the period with the longest drought of the last 36 years.

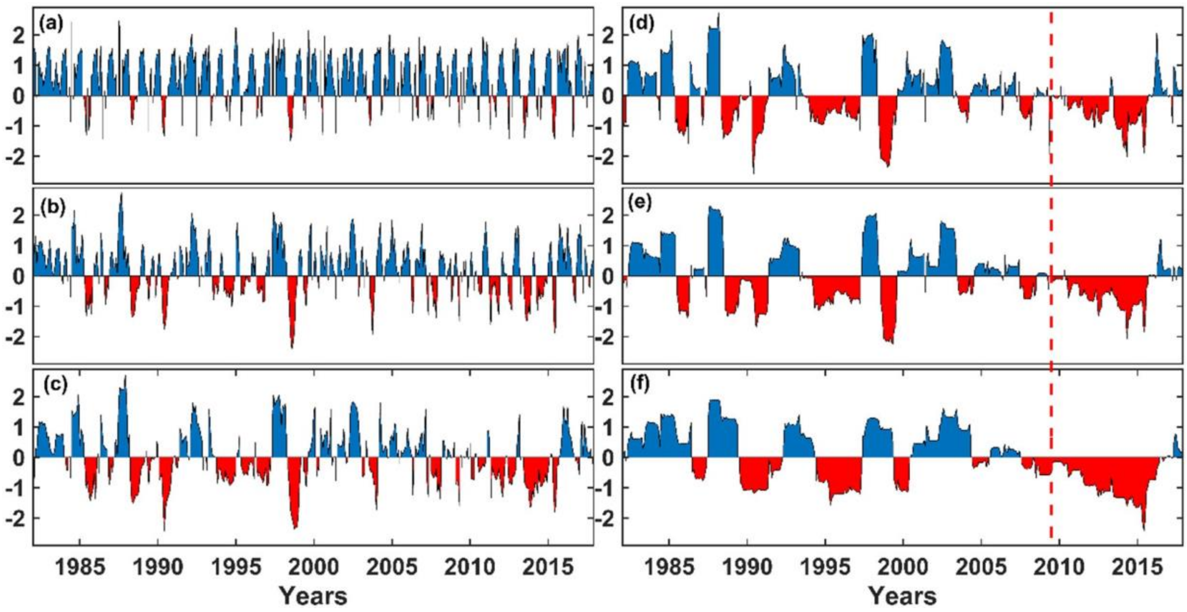

Figure 3.6. Standardized Precipitation Index (SPI) time series from 1982 to 2017, (a) SPI1, (b) SPI3, (c) SPI6, (d) SPI9, (e) SPI12, and (f) SPI24.

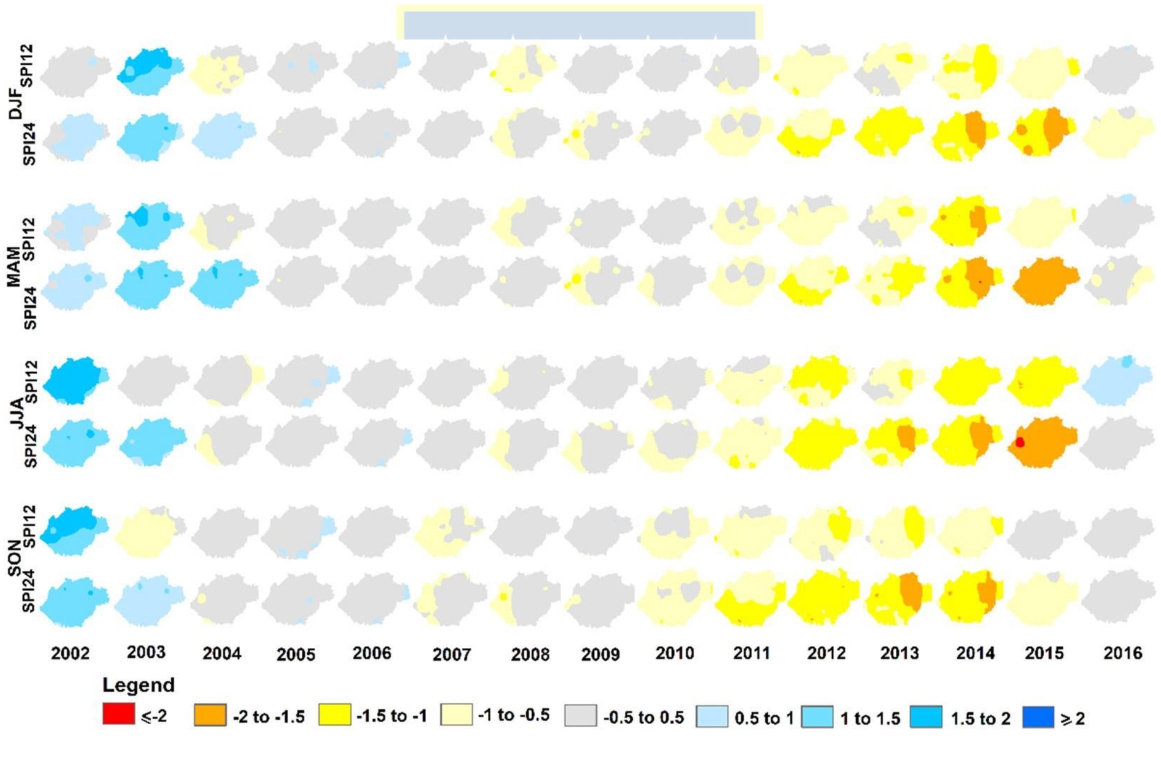

Figure 3.7. Spatial extent of SPI 12 and SPI 24 in the study area from 2002 to 2016 in summer (DJF), autumn (MAM), winter (JJA), and spring (SON).

3.1.2 GW and Drought

As previously verified, the most critical drought period was between 2010 and 2015, mainly in SPI 9, 12, and 24, which is reaffirmed in Figure 3.8, where each SPI scale is compared with the standardized GW values. In this case, the rainfall deficits as seen through SPI values present a relationship with the decrease in standardized GW values, which is strongest between 2010 and 2015. While the

SPI values do not show different behaviors between the watersheds, the standardized GW values are lower in the Ligua watershed. This demonstrates that other factors such as GW rights, GW overexploitation for irrigation, and land-use change could have a greater influence on GW depletion than decreased rainfall. This idea or assumption will be addressed in the following sections.

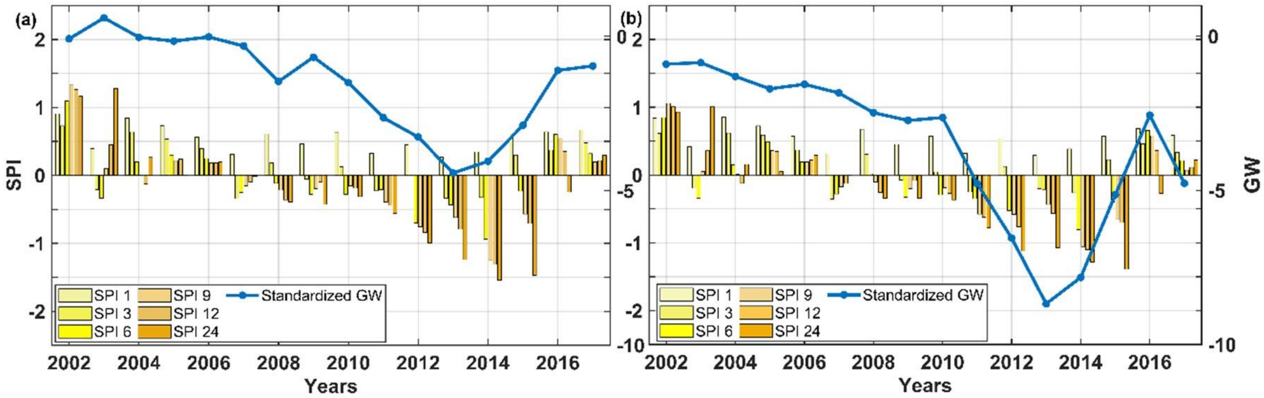

Figure 3.8. Annual standardized GW and annual SPI at different scales in (a) Petorca watershed and (b) Ligua watershed from 2002 to 2017.

3.2 NDVI Time Series Data Analyses

The NDVI time series (Figure 3.9) present a very slight decrease between 2009 and 2015; thus, vegetation is also affected in this period of aquifer depletion, which is also found in previous analysis. The NDVI is greater starting at 800 m in comparison with the rest of the area, which is a result of farmland and the effect of irrigation. The values in the watersheds vary between 0.24 and 0.49, decreasing to 0.24 in 2014, while up to 800 m, they range between 0.30 and 0.67, with lower values also found in 2014.

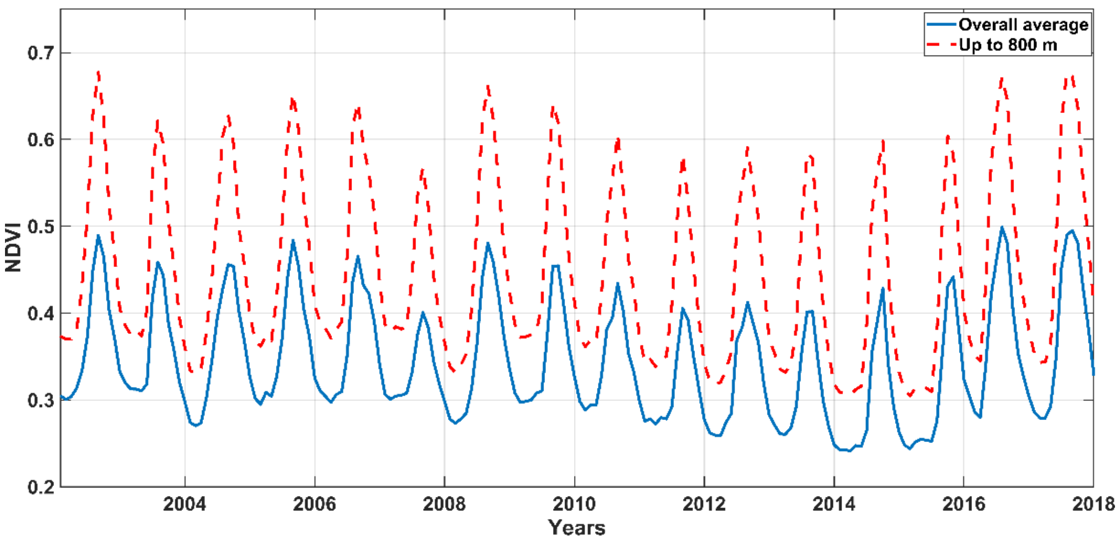

Figure 3.9. Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) time series in the watersheds and land up to 800 m from 2002 to 2017.

3.3 LULCC 2002–2017. Natural and Human Implications

The land-use classifications (Figure 3.10) present good precision (>90%) (Table 3.3), with a general Kappa index of 0.91. The most difficult-to-classify uses were plantations of fruit trees such as avocado, due mainly to the similarity of their spectral signatures. Meanwhile, the uses that allowed the best discrimination were bare soil and water as their signatures are not particularly difficult to separate and classify. The LULCC (Land Use/Land Cover Change) up to 800 m is shown as it is the most important zone for the study area since the agricultural area is concentrated there. Regarding the distribution of the land-use categories, the predominance of native covers in the upper parts of the watershed, mainly shrubs and native forest, associated with sclerophyll forest, can be observed, while the valley regions were found to be dominated mainly by avocado, fruit tree, agricultural, and urbanization uses.

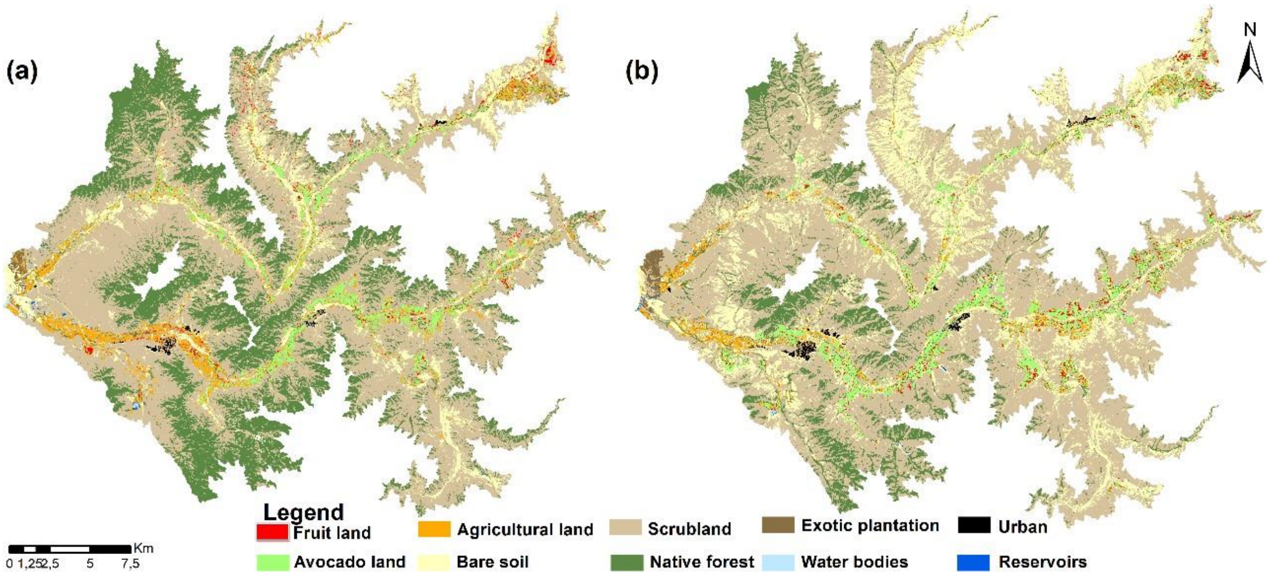

Figure 3.10. Land-use/land-cover change in the Ligua and Petorca valleys between 2002 and 2017 (a and b).

Table 3.3. General classification precisions.

Classified Image	Overall Accuracy	Kappa
21 March 2002	93.28	0.92
21 March 2002	92.73	0.92
20 March 2002	93.12	0.92
1 January 2017	90.88	0.90
1 January 2017	91.64	0.90

Scrubland was the largest land-use, with 83,974 ha in 2002 and 90,208 ha in 2017. Native forest also occupied a large area. The scrubland is made up of sclerophyll arborescent species and is found near prairies or areas of prairie crop rotation, while native forest such as Mediterranean sclerophyll forest and Mediterranean spiny forest is a vegetation type that is denser [61]. Both uses decreased in the analyzed period. Reservoirs and bodies of water are not identified at the scale of the map, but were considered in this study as they are an important cover to analyze in the context of the investigation. Reservoir area increased from 102 ha a 121 ha, meaning that they continued to be built during the analyzed years despite the drought. The total agricultural area increased, but this growth was small and the individual behavior in each watershed was very different. The avocado (*Persea americana Mill*.) use was identified as a separate category due to the importance of the crop for the study area in economic and political terms, as well as its water demand. It accounted for 5023 ha in 2002 and 7518 ha in 2017.

Table 3.4 shows the net change in land uses. Fruit trees, avocado, bare soil, scrubland, exotic plantations, reservoirs, and urban zones presented increases in area, while agricultural land, native forest, and water bodies decreased. Bare soil was the use with the biggest gain, which means that its area increased, mainly at the expense of native forest, thereby decreasing the moisture retention of the soil and infiltration. Reservoirs had a net change of 19 ha as the gains were greater than the losses. Although fruit tree plantations decreased in some areas, their gains far exceeded their losses; however, avocado had a large positive net change (2 495 ha) compared to the other agricultural areas. There were differences in these land-use changes between watersheds. Reservoirs increased and agricultural area decreased in Petorca, while only farmland dedicated to traditional crops and prairie crop rotation decreased in Ligua. In the latter watershed, fruit tree plantations increased by 631.8 ha and avocado plantations by 2 623.6 ha. Most significant was the increase in the bare soil area in both watersheds and the large avocado increase in Ligua compared to other farmland, unlike in Petorca, where the area of this crop decreased by 128 ha (Figure 3.11).

Table 3.4. Land-use change between 2002 and 2017.

Land-Use and Land-Cover Category	Changes (Ha)		Net Change (Ha)
	Losses	Gains	
Frutales	-1,252	1,669	417
Paltos	-2,567	5,062	2,495
Agricola	-4,436	1,574	-2,863
Descubierto	-5,865	20,541	14,676
Matorrales	-21,240	27,474	6,234
Bosque nativo	-23,607	2,427	-21,180
Plantacion	-174	244	69
Agua	-45	0	-45
Embalse	-92	112	19
Urbano	-27	204	177

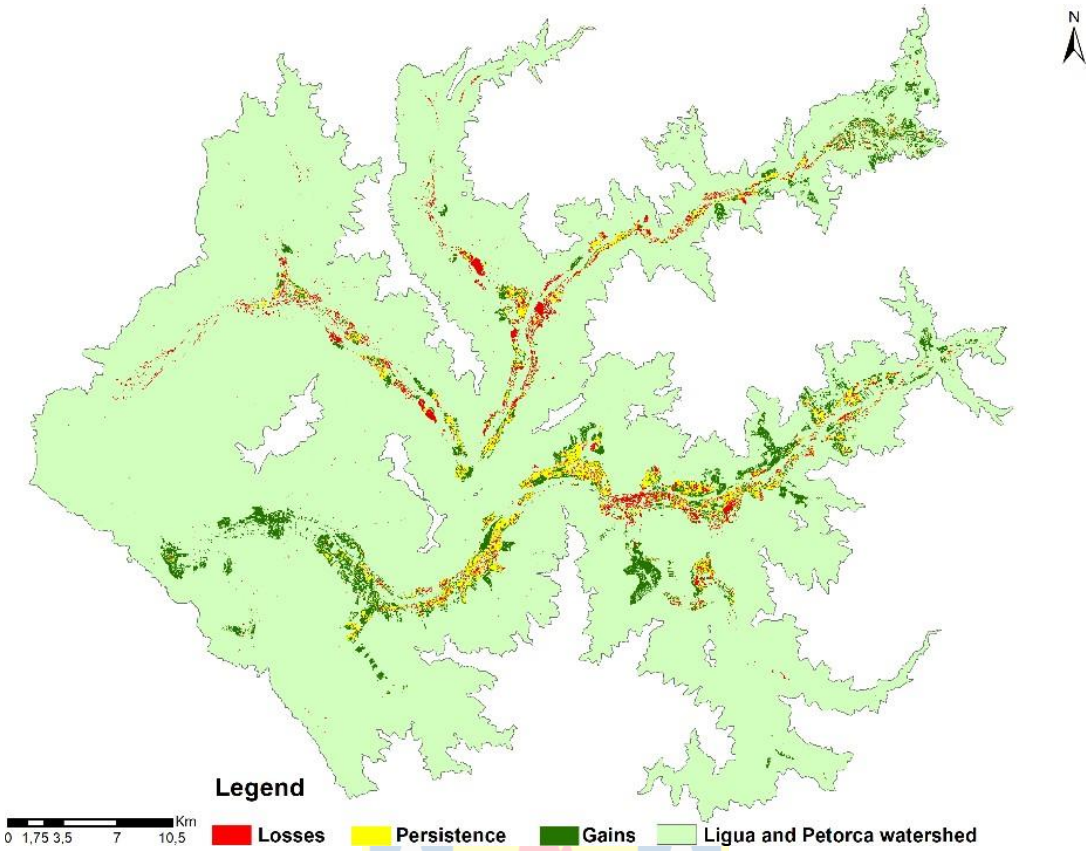

Figure 3.11. Gains, persistence, and losses of avocado land.

3.4 GW Rights

The GW rights granted by the DGA (Figure 3.12) have contributed to the decrease in GW levels. Rights continued to be granted during the years analyzed in this study and the number of rights granted was greatest in 2006 and 2008. Use rights (ND) account for the great increase of rights in this analyzed time period because they are the new rights granted.

Although in recent years—since 2015—the number of new rights granted has decreased, possibly due to measures taken by the authorities, and these adjustments were made somewhat late considering the effect that they could have had on GW depletion. According to the data, most of the rights are consumptive for agricultural irrigation. Although this analysis does not consider values by drainage basin, as there is not enough information to place each right geographically and the data are available at a municipality level, these results show—at the scale of the entire study area—that the number of rights and associated streamflow are related to the decrease in GW. The number of new rights increased in all municipalities and it was also verified that most are concentrated among families dedicated to avocado exports.

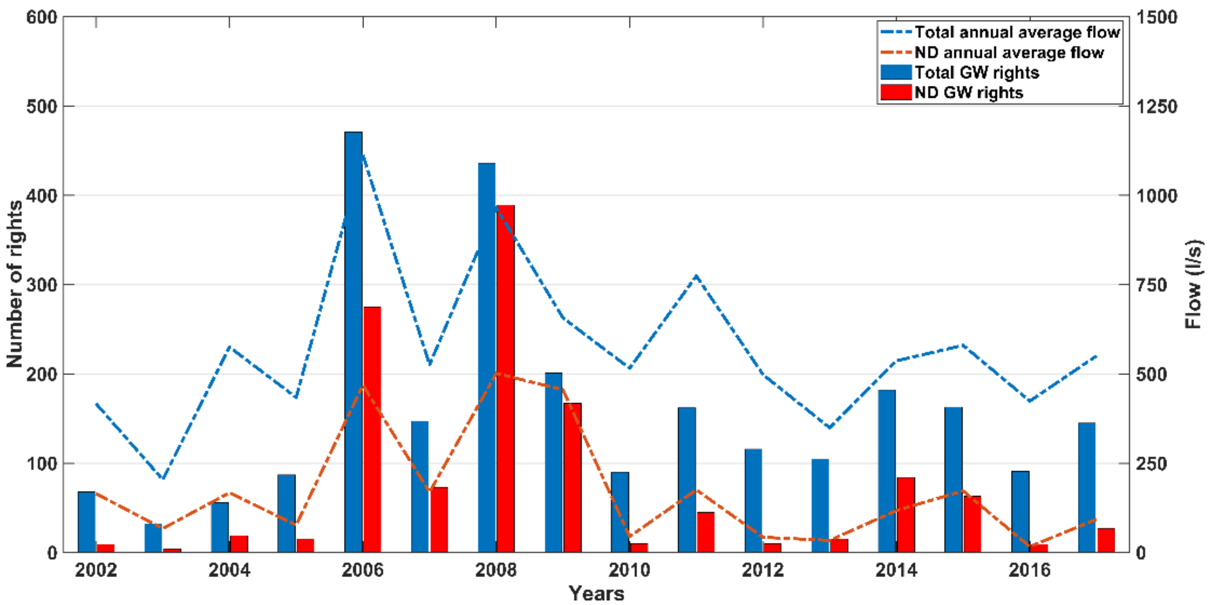

Figure 3.12. Number and average streamflow of GW rights between 2002–2017.

3.5 Statistical Analyses

3.5.1 GW, Rainfall, and Vegetation Trend Tests

The trend analysis of the non-parametric tests is shown in Table 3.5; the results indicate a significant decrease in GW (in 75% of the wells) and most of the Ligua watershed. GW decreases by season were also significant. The Pettitt test showed the greatest number of significant points in 2009, but each abrupt change in the data series may be determined by local anthropogenic factors. Rainfall was also analyzed during 1980–2017, according to a period established by the World Meteorological Organization [62]. The results showed that it also decreased, but not to a statistically significant extent; therefore, it cannot be stated that there was a trend in the series. Nor were there any abrupt changes during these 36 years; rather, rainfall decreased slightly and the decrease in 2009 and 2010 was also too small to generate abrupt changes. In addition, with the tests applied to the NDVI, it cannot be stated that there is a trend in the series.

Table 3.5. Trend analyses of annual average GW by well and season during 2002–2017

PETORCA					LIGUA				
Wells and Seasons	**Mann Kendall and Sen's Slope**		**Pettitt**		**Wells and Seasons**	**Mann Kendall and Sen´s Slope**		**Pettitt**	
	***p*-Value**	**Slope Value**	***p*-Value**	**Change Point**		***p*-Value**	**Slope value**	***p*-Value**	**Change Point**
La Canela	**0.03**	−0.40	0.11	2007	La Ligua	**0.00**	−0.28	**0.01**	**2006**
H. Viejo	**0.00**	−0.24	**0.00**	**2009**	Placilla	**0.00**	−0.33	**0.00**	**2008**
Pullancón	0.26	−0.13	0.18	2009	Alicahue	**0.00**	−0.38	**0.00**	**2008**
Longotoma	**0.00**	−0.31	**0.00**	**2009**					
Pedegua	**0.00**	−0.43	**0.00**	**2007**	S. Lorenzo	**0.00**	−0.64	**0.05**	**2007**

S. Manuel	**0.00**	−0.27	**0.00**	**2008**	Papudo y Zapallar	**0.00**	−0.33	**0.00**	**2010**
S. Marta	0.16	−0.18	0.34	2009					
S.Bellavista	**0.01**	−0.14	**0.03**	**2010**	F.Montegrande	**0.00**	−0.39	**0.00**	**2009**
El Boldo	0.06	−0.18	0.17	2005					
Piwonka	**0.02**	−0.20	**0.00**	**2009**	Pahiuen	**0.00**	−0.34	**0.00**	**2010**
L. Silva	**0.00**	−0.20	**0.00**	**2009**	Aconcagua	0.37	−0.10	0.22	2006
O. Chalaco	**0.01**	−0.29	**0.02**	**2009**					
DJF	**0.00**	−0.32	**0.00**	**2009**	DJF	**0.02**	−0.19	**0.02**	**2009**
MAM	**0.00**	−0.26	**0.00**	**2009**	MAM	**0.00**	−0.39	**0.00**	**2008**
JJA	**0.01**	−0.24	**0.03**	**2007**	JJA	**0.00**	−0.43	**0.00**	**2007**
SON	**0.00**	−0.26	**0.01**	**2007**	SON	**0.00**	−0.29	**0.00**	**2009**

Note: Bold values represent statistical significance at *p*-value < 0.05.

3.5.2 GW Correlation with Rainfall, Drought, Vegetation, and Human Factors. Cross Correlation and Cluster Analyses

Figure 3.13 shows the Pearson correlation coefficient values between the studied variables and GW by hydrogeological sector. The analysis was not performed in sectors 2, 9, and 11 due to the absence of wells there. The highest coefficients found were with SPI 12 and 24, oscillating between 0.46 and 0.68 at the 12-month scale and 0.52 and 0.80 at the 24-month scale, which reflects the relationship between GW and hydrological drought. In sector 7 (Ligua central valley), the correlations with all variables were low, which could be due to local human factors such as excessive GW extraction. The values with rainfall were very low (<0.20), meaning a low correlation with GW. There was a low, negative correlation in sector 11, but it is located near the coast and its rainfall behavior is determined by oceanic effects such as sea breezes, which promote the formation of fog and coastal clouds, leading to a cooler, wetter coastal climate [61].

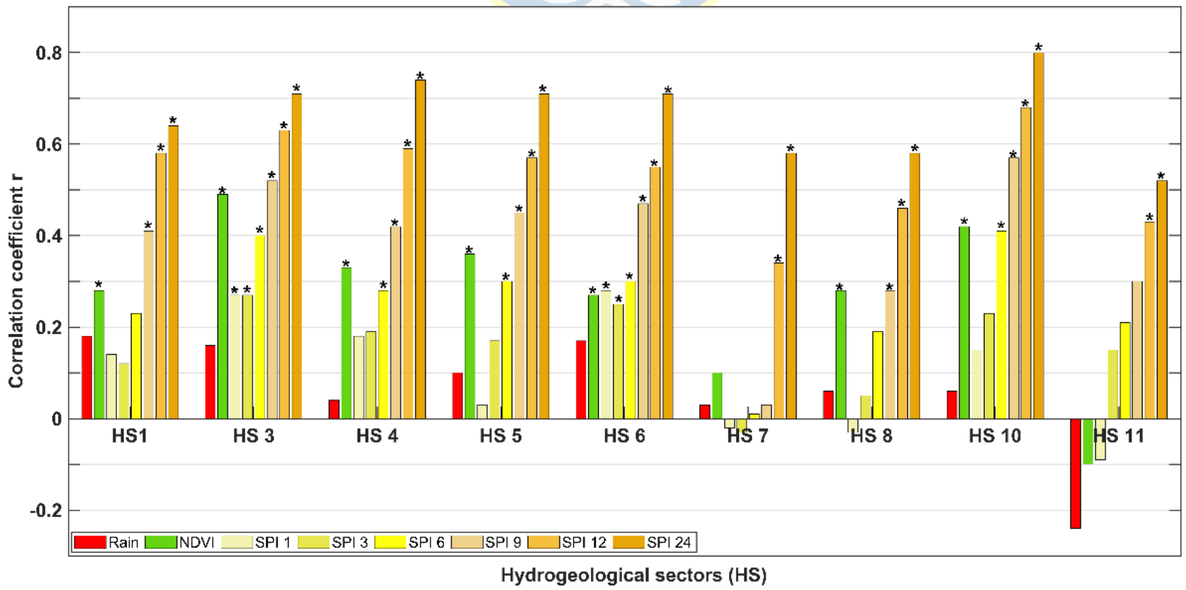

Figure 3.13. Correlation with GW by hydrological sector (HS) of time series variables (Rainfall, NDVI, SPI1, SPI3, SPI6, SPI9, SP12, and SPI24), significance level of 0.05, from 2002 to 2016. Statistical significance is indicated by (*).

The NDVI-GW correlation values were higher than the GW-rainfall correlation values, even reaching 0.49 in sector 3 (upper eastern of Petorca), and significant in most cases (Figure 3.13). These GW-NDVI values are high considering that the study area is a semi-arid zone, where a low correlation between vegetation and GW is expected; this result reflects the presence of farmland. In general, the coefficients with the SPI and NDVI were statistically significant, unlike with rainfall.

Monthly cumulative new GW rights were also correlated with average GW levels (only at a municipal level). The value was −0.70 for number of rights and −0.71 for annual average streamflow; thus, a high, significant inverse correlation was found, which reaffirms that human activity affects GW levels.

Cross Correlation

To investigate if the delayed effect of rainfall and vegetation on GW levels was important, they were cross correlated for up to six subsequent months (time lag of 1 to 6 months). In some cases, the GW-rainfall correlation values increased very little in the first months of time lag, sometimes even decreasing (Figure 3.14). The GW-NDVI correlation coefficient values continued to be greater than those of GW-rainfall and were also greater than in the correlation without time lag. In summary, the correlations were slightly more influenced by the time lag, mainly GW-NDVI.

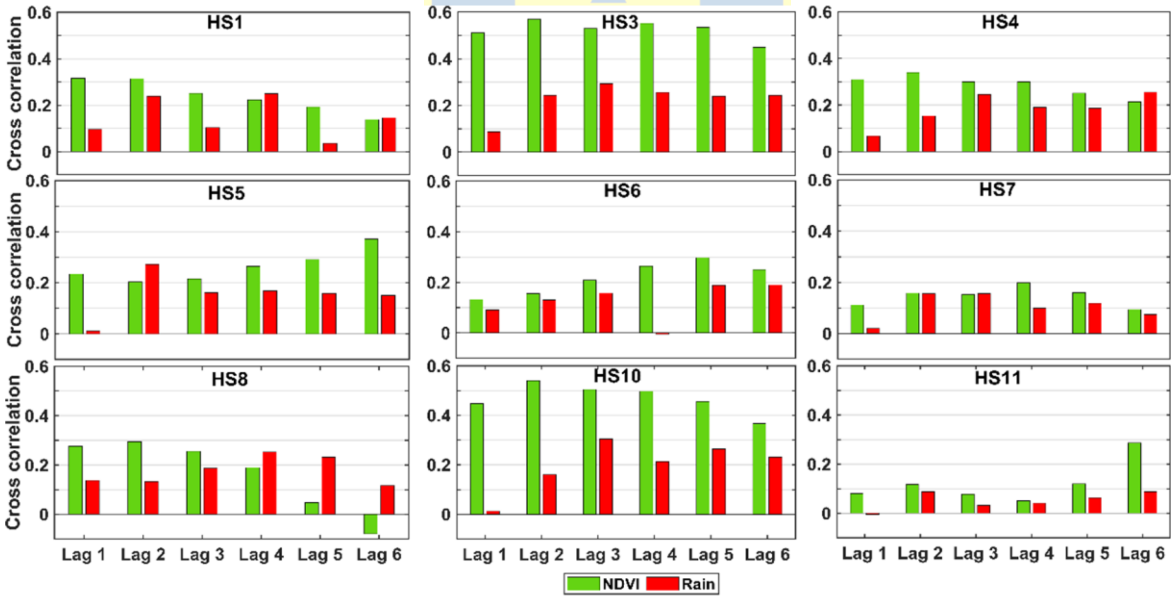

Figure 3.14. Time lag period cross correlation between GW and rain and NDVI by the hydrogeological sector (SH) from 2002 to 2016.

Cluster Analysis

The cluster analysis grouped the wells into three groups or classes (Table 3.6). The first class of five wells, which is located in areas with a large increase in avocado crop and urban areas, presented high GW decreases. The second group

(12 wells) included the wells with less of a decrease in GW and their location did not show an association with land use. The third group consists of the O. Chalaco, Aconcagua, and S. Lorenzo wells (Figure 3.5), which were those that presented the highest levels of GW decrease as of 2010 and which are located in large agricultural areas where avocado land increased considerably between 2002 and 2017.

Table 3.6. Results by class through k-means clustering.

[1]Class	Objects	Sum of Weights	Within-Class Variance	Minimum Distance to Centroid	Average Distance to Centroid	Maximum Distance to Centroid
1	5	5	40.82	4.33	5.52	8.34
2	12	12	23.87	2.34	4.34	8.29
3	3	3	142.03	7.38	9.59	11.35

[1] **Class 1:** La Canela, Pedegua, L. Silva, La Ligua, and Pahiuen. **Class 2:** H. Viejo, Pullancón, Longotoma, S. Manuel, S. Marta, S.A. Bellavista, El Boldo, Piwonka, Placilla, Alicahue, Montegrande, and Papudo y Zapallar. **Class 3:** O. Chalaco, S. Lorenzo, and Aconcagua.

4. Discussion

4.1 Assessment of GW Depletion and its Implicants

GW depletion in the 2002–2017 period was evident when its behavior by well in the two watersheds was analyzed. A greater decrease in some wells in the Ligua central valley, a reflection of local factors, was observed; however, rainfall and the SPI results do not indicate spatial and temporal differences between the watersheds. The 2009–2015 period was the most critical and a relationship between GW-SPI was found, mainly at the 9–24-month scales, indicating a moderate hydrological drought, but the longest in the last 36 years. This drought is consistent with that addressed in the study carried out by Garreaud et al. [63] in south-central Chile, a megadrought lasting from 2010 to 2015. Other investigations have delved into the climate dynamics of this drought [16,64] and analyzed the negative impacts on the hydrological regime of Chile [16,65,66]. The most critical years were 2012 to 2014 in terms of GW, rainfall, and the NDVI and a review of the fruit registry of the Office of Agriculture Studies and Policies (ODEPA, for its acronym in Spanish) between 2008 and 2014 confirmed that in 2014, the fruit-growing area in both watersheds had decreased, possibly due to the drought or more likely due to increases in avocado crops at the expense of other fruits; however, GW for irrigation continued to be extracted.

The results demonstrate that there is a relationship between the GW decrease and the drought, although it cannot be stated that there is a trend in rainfall behavior related to the significant GW decrease; however, the statistical correlation between GW and rainfall was very low. The standardized GW values showed spatial difference between the two watersheds, while the SPI was spatially homogeneous. In Ayala et al. [19], there was also discussion of the decrease in well levels and the difficulty of quantifying the actual amount of water level variation using historical pumping data on the area as it was undergoing irregular extraction of water resources. Celedón [20] stated that 2010 was the year with the greatest GW use for irrigation as it was the year with the greatest amount of planted farmland and lowest surface water availability. These ideas show that a large quantity of water was being extracted in the studied valleys and confirm the results.

It was possible to confirm that the agricultural factor played the most important role in aquifer depletion. The drought affected both valleys with the same intensity, but Ligua crops were maintained and avocado trees continued to be planted and were expanded into the hills (Figure 3.15a–c). In this, watershed irrigation and GW extraction continued despite recharge by rain decreasing, without regard for aquifer sustainability. Petorca was slightly more affected by the drought and the effects of agricultural areas on GW were lower, as can be observed in Figure 3.15f. This photograph was taken by the authors in the Petorca valley, where it was confirmed that many agricultural areas had been abandoned. In Figure 3.15d, avocado growing on a hill in Petorca is seen, showing that although some areas were lost, many were maintained. Nonetheless, water rights continued to be granted and reservoirs increased (Figure 3.15e). These reservoirs are located near the cultivated areas to guarantee irrigation. Many of these reservoirs were built by the Chilean government to “mitigate” drought effects, according to Bolados et.al. [14] and Panez-Pinto et al. [17], however based on the results of this investigation, this measure taken by the government could have had the opposite effect by contributing to greater groundwater extraction to keep the reservoirs supplied, considering that the Ligua and Petorca watersheds are characterized by semi-arid conditions and low annual rain, in addition to being affected by a prolonged drought process.

In addition, it was confirmed that the wells with the greatest decreases were those located in zones where avocado growing areas increased or were maintained. Avocado is a fruit with a tropical origin that requires a large water supply throughout the year for adequate vegetative and productive growth [67–69]. The water requirements for achieving maximal yields of this crop in a mediterranean region are over ~7500 m^3 ha^{-1} $year^{-1}$, according to [70]; therefore, the increase or maintenance of this crop has repercussions for GW use and extraction.

Other studies have investigated the situation in the Petorca Province and Ligua watershed regarding avocado growing and water rights. In [14,15,22,23], the conflicts that were taking pace over the human right to water, agribusiness, and the usurpation of GW in Petorca were analyzed. Bolados et al. [14] carried out a study on the beginnings of avocado growing in Petorca and how the province became an exporter to large international markets such as China and Europe, as well as an analysis on the great inequalities regarding water rights stemming from the Water Code, as a result of legislation imposed during the military dictatorship. The results of these studies are reaffirmed in this work, which found a large area of avocado compared to other crops, with its expansion in valleys and hills and the continuous granting—in perpetuity and at no cost—of water rights, which were highly correlated to aquifer depletion. Although the number of rights granted decreased in recent years, probably due to measures taken by the government and the DGA, the effect is still noticeable and cumulative, with repercussions on GW depletion.

Through the analysis of data records of GW rights, it was confirmed that a large part of the rights granted belonged to entrepreneurs dedicated to the cultivation of avocado and lemon, as mentioned in Bolados et al. [14].

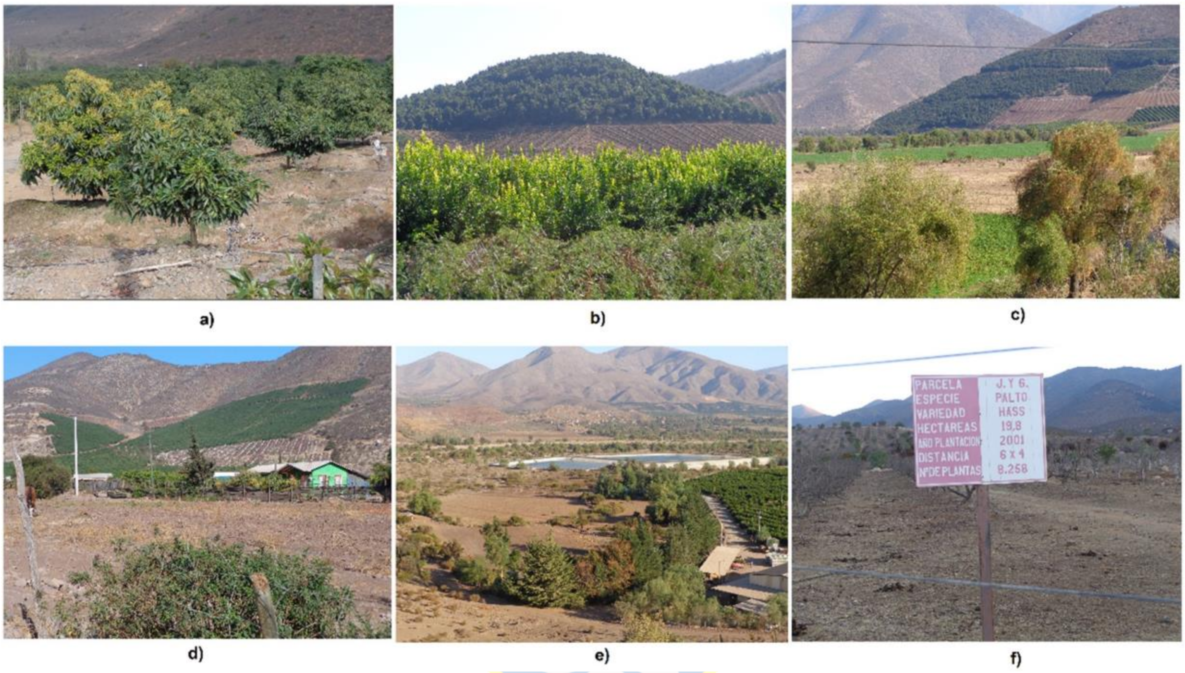

Figure 3.15. Photographs taken by the authors of the study area; (a–c) avocado land in Ligua watershed, and (d) avocado land, (e) reservoirs, and (f) abandoned avocado land in Petorca watershed.

4.2 GW Resources Management in the Ligua and Petorca Watersheds

GW is a resource for current and future generations and its sustainable use is possible only through sustainable GW resources management, as explained in [1,13]. The results showed GW overexploitation as there is an imbalance between availability and extraction. Therefore, GW management in the Ligua and Petorca watersheds is not sustainable. For several decades, with the beginning of agribusiness and the privatization of water in the area [14], water resources management has been absent despite great efforts made by inhabitants and social organizations linked to the human right to water such as the Movimiento de Defensa del Agua, la Tierra y el Medioambiente (Water, Land and Environmental Defense Movement; MODATIMA, for its acronym in Spanish), as well as the DGA. This agency has used various regulatory mechanisms such as the creation of

Groundwater User Communities and declarations of water scarcity and restriction zones [16,20,21], but they have not been effective.

It is important to establish scientific and political agreements between academic and governmental agencies inside and outside the watersheds. A new reform of the Water Code must include environmental streamflows and new, effective regulations that guarantee that the supply capacity of aquifers does not exceed their sustainable volume. New water management mechanisms that ensure greater power for regions and local authorities as regulating agents and improvements in agricultural practices amid drought scenarios are necessary. The Chilean government and the DGA must implement effective actions to equitably guarantee the human right to water. There also must be more inspections of water use and sanctions in the event of violations of groundwater rights. Additionally, GW communities must be supported to guarantee increased user interest and greater functioning of these already established organizations, since they were created to achieve GW management, according to [71] and [23]. All these proposed measures can contribute to GW resources management.

To continue delving into this issue of GW loss, more interdisciplinary studies that include citizen perceptions are recommended to contribute to decision-making. Providing these results to local, regional, and national governments could improve the water management. In addition, further in-depth study of land-use dynamics before, during, and after the studied period is needed.

5. Conclusions

The GW level presented a statistically significant decreasing trend, which was greater in the Ligua watershed wells, while the decrease in rainfall was not statistically significant. Starting with SPI 6, a drought period between 2010 and 2015 was observed, which was more evident in SPI 12 and SPI 24, which showed a hydrological drought classified as moderate but very long. A relationship between rainfall and GW was demonstrated, but the SPI and rainfall analysis did not show spatial differences between the two watersheds. The statistical analysis offered an accurate view of the relationship between variables. The GW-SPI (12 and 24) correlations were high, which showed a relationship between GW depletion and hydrological drought. However, GW-rainfall correlations were low; therefore, although rainfall is the main recharge source of GW in the study area and aquifer depletion was mostly influenced by human factors. In addition, the GW-NDVI correlation was greater than that of GW-rainfall, reflecting the influence of irrigation, and the correlation between GW and GW rights was very high. The land-use change analysis allowed the conclusion to be drawn that the areas with the greatest GW decreases were those in which avocado growing increased. The Ligua watershed was more affected, with an increase of 2623.6 ha and a greater GW decrease, while in Petorca, the avocado area decreased very little (128 ha); however, it also presented areas in which the area dedicated to this crop increased or was maintained, along with an increase in reservoirs.

The increase in high-water demand or the overgranting of GW rights, associated with overexploitation by agriculture due to increases in the avocado-growing area, irrigation, and reservoirs, along with the lack of sustainable water resources management, confirmed that groundwater depletion was mostly influenced by human factors regarding climatic factors.

The management measures proposed and the results obtained through an interdisciplinary approach, which reflect water systems that cannot support the high demand of agriculture in semi-arid conditions, the impacts of drought, and the need for more sustainable GW resources management, all against the backdrop of a private water management model, are the main lessons to be learned from this research.

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CAPÍTULO IV. AGOTAMIENTO DE LAS AGUAS SUBTERRÁNEAS Y ECOSISTEMAS DEPENDIENTES EN LAS CUENCAS LA LIGUA Y PETORCA

En el presente capítulo se muestran los resultados de un segundo artículo científico en estado ***Enviado*** a la revista ***Science of the Total Environment*** de la base de datos **WoS**.

Duran-Llacer, I.; Arumí, J.L.; Arriagada, L.; Aguayo, M.; Rojas, O.; González-Rodríguez, L.; Rodríguez-López, L.; Martínez-Retureta, R.; Oyarzún, R.; Sudhir, K. (***Enviado***). A new method to map potential groundwater-dependent ecosystem zones in semi-arid environments: A case study in Chile. *Science of the Total Environment*.

IV. 1 Resumen

El uso de las aguas subterráneas (GW) se ha intensificado en las últimas décadas y la integridad ecológica de los Ecosistemas Dependientes de las Aguas Subterránea (GDE) se ha visto amenazada. El estudio de los GDE es limitado, por lo que es necesario enfoques integrados e interdisciplinarios que garanticen su monitoreo y gestión ante los cambios climáticos y antrópicos actuales. Un nuevo método geoespacial con un enfoque integrado y temporal fue desarrollado mediante una aproximación multicriterio teniendo en cuenta el criterio de experto, Remote Sensing-GIS y trabajo de campo para mapear Zonas Potenciales de Ecosistemas Dependientes de las Agua Subterránea (GDEPZ). Se realizó una encuesta a expertos para asignar grado de importancia a los distintos parámetros geoespaciales y el mapeo se llevó a cabo empleando 14 parámetros. Los parámetros reclasificados se normalizaron en una escala de 1 a 5, según la alta o baja probabilidad de presencia de GDE. La validación se realizó con trabajo de campo y los cambios espacio-temporales ante el nivel cambiante de las GW fueron evaluados a través del Índice de Vegetación de Diferencia Normalizada (NDVI) de verano. Se obtuvieron dos mapas de GDEPZ en 2002 y 2017, y la superficie de las zonas altas y muy altas disminuyeron en 31 887 ha (7.43 y 0.72 %, respectivamente). Los parámetros temporales más sensibles a los cambios espacio-temporales empleados en el análisis multicriterio fueron la lluvia y el cambio del uso del suelo, siendo la lluvia el de ligeramente mayor influencia. Se demostró además que los ecosistemas identificados disminuyeron o fueron afectados por el agotamiento de los acuíferos (NDVI-GW, r Pearson ≥ 0.74). Este método validado permite mapear y analizar a escala anual los cambios espacio-temporales de los GDE, y es transferible a otros ambientes áridos y semiáridos.

Palabras claves*:* Ecosistemas Dependientes de las Aguas Subterráneas, opinión de experto, SIG, Teledetección, análisis multicriterio, NDVI

IV.2 A new method to map potential groundwater-dependent ecosystem zones in semi-arid environments: A case study in central Chile

Iongel Duran-Llacer [a,b*], José Luis Arumí [b], Loretto Arriagada [b, c], Mauricio Aguayo [a], Octavio Rojas [a], Lisdelys González-Rodríguez [d], Lien Rodríguez-López [e], Rebeca Martínez-Retureta [b], Ricardo Oyarzún [b, f, g], and Sudhir Kumar [h]

a Facultad de Ciencias Ambientales y Centro EULA-Chile, Universidad de Concepción, Víctor Lamas 1290, Concepción 4070386, Chile
b Centro de Recursos Hídricos para la Agricultura y la Minería (CRHIAM), Universidad de Concepción, Concepción 4070411, Chile
c Facultad de Ingeniería, Universidad del Desarrollo, Avenida plaza 680, Las Condes, Chile
d Facultad de Ingeniería, Universidad de Concepción, Víctor Lamas 1290, Concepcion 4070386, Chile
e Facultad de Ingeniería y Tecnología, Universidad San Sebastián, Lientur 1457, Concepción 4030000, Chile
f Departamento Ingeniería de Minas, Universidad de La Serena, Benavente 980, La Serena, Chile
g Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Raúl Bitrán 1305, La Serena, Chile
h K. Banerjee Centre of Atmospheric and Ocean Studies, University of Allahabad, Prayagraj 211002, India

Corresponding author * ioduran@udec.cl

Highlights

- A new geospatial method with an integrated and temporal approach was developed through a multicriteria approximation to map potential groundwater-dependent ecosystem zones (PGDEZ).
- This validated method is based on conventional geospatial information, topographic parameters, multispectral indices, and climate variables.
- Spatio-temporal changes in PGDEZ between 2002 and 2017 were analyzed.
- The influence of rainfall on the spatio-temporal changes in these ecosystems was slightly greater than that of human activities.

Abstract

Groundwater (GW) use has intensified in recent decades, threatening the ecological integrity of groundwater-dependent ecosystems (GDEs). The study of GDEs is limited; therefore, integrated and interdisciplinary approaches that guarantee their monitoring and management amid current climate and anthropogenic changes are needed. A new geospatial method with an integrated, temporal approach was developed through a multicriteria approximation, taking into account expert opinion, remote sensing-GIS, and fieldwork to map potential groundwater-dependent ecosystem zones (PGDEZ). A survey of experts was conducted to assign degrees of importance to the various geospatial parameters, and the mapping was carried out using 14 parameters. The reclassified parameters were normalized on a scale of 1 to 5 according to the degree of probability of the presence of GDE. The validation was carried out through fieldwork and the spatio-temporal changes amid changing GW levels were assessed using the summer normalized difference vegetation index (NDVI). Two PGDEZ maps were obtained, for 2002 and 2017, between which the high- and very-high-probability areas decreased by 31,887 ha (7.43% and 0.72%, respectively). The most sensitive temporal parameters to spatio-temporal changes used in the multicriteria analysis were rainfall and land-use change, with rain exerting a slightly greater influence. It was also demonstrated that identified ecosystems decreased in area or were affected by aquifer depletion (NDVI-GW, r Pearson ≥ 0.74). This validated method allows spatio-temporal changes in GDE to be mapped and analyzed at an annual scale and is transferable to other arid and semi-arid environments.

Keywords

groundwater-dependent ecosystems, expert opinion, GIS, remote sensing, multi-criteria analysis, NDVI

1. Introduction

Groundwater (GW) is the greatest reserve of liquid freshwater on the planet (Eamus et al., 2015) and the main water resource in arid and semi-arid regions (Liu et al., 2021). Its use has intensified in recent decades, and there is a growing risk of depletion in most of the world. It is estimated that 20% of aquifers are being overexploited (Mossa et al., 2019). GW plays a crucial role in sustaining certain types of aquatics, terrestrial, and coastal ecosystems, as well as their associated landscapes. It provides an input flow that maintains the water level, temperature, and chemistry necessary for the flora and fauna it supports (Brown et al., 2011; Howard and Merrifield, 2010). It supplies the base flow in late summer for many rivers and creates seeps necessary for aquatic species during high-temperature periods. It is also the only source for springs and ecosystems that host important but often little-known biodiversity (Kløve et al., 2011a). Therefore, GW is a significant factor in the ecological integrity of many ecosystems, particularly those known as groundwater-dependent ecosystems (GDEs) (Kløve et al., 2014a; Liu et al., 2021).

GDEs are ecosystems that require the presence or support of GW to maintain their composition, structure, and ecological function (Barron et al., 2014; Eamus et al., 2006), whether continually or intermittently, in order to maintain their plant and animal communities, processes, and ecosystem services (Doody et al., 2017; Glanville et al., 2016). They are divided basically into terrestrial and aquatic systems, including rivers (aquatic, hyporheic, and riparian habitats), lakes, forests and bushes, prairies, wetlands and springs, as well as estuarine and coastal ecosystems (Kløve et al., 2011a; Liu et al., 2021; Zurek et al., 2015). GDEs provide great ecological and socioeconomic value, but insufficient GW input can threaten the variety of associated ecosystem services, which include biodiversity, flood filtration and mitigation, erosion prevention, food production, recreation, and tourism (Doody et al., 2017; Smith et al., 2020).

The primary GW conservation and management efforts are centered on its protection for different uses, but the focus on GDEs has been rather limited (Kløve et al., 2014a). Great efforts are required to understand the close relationship between GW and the ecosystems they sustain as an essential indicator to link human and ecological water needs (Pérez Hoyos et al., 2016). These needs appear as different uses, but must be managed in an integrated, multidisciplinary manner (Kløve et al., 2011b; Zurek et al., 2015). In addition, because human beings increasingly depend on GW for irrigation and the drinking water supply, GDEs are threatened, especially during the dry months of summer and in droughts in regions with mediterranean climates. Therefore, practical approaches that guarantee efficient monitoring to protect GDEs in changing conditions are needed, within current sustainable GW management policies (Rohde et al., 2019). However, to characterize their degree of GW dependence and their ecological response and achieve effective management, first it is necessary to ascertain the locations and areas of these ecosystems (Marques et al., 2019; Pérez Hoyos et al., 2016).

Most studies on GDEs have been centered on their conceptualization, management, and ecohydrological relationships (De La Hera et al., 2016; Eamus et al., 2006; Erostate et al., 2020), while others have used some tools to carry out spatial analyses of them, such as remote sensing and GIS (Pérez Hoyos et al., 2016). In Doody et al. (2017) and Glanville et al. (2016), in addition to the geospatial techniques mentioned above, expert opinion was used to suitably integrate a conceptual understanding of these ecosystems. However, the greatest efforts have focused mainly on the analysis of GW-dependent vegetation ecosystems, in which field validation has been little used (Dabovic et al., 2019; Huntington et al., 2016; Marques et al., 2019). These investigations have not been of a temporal nature in the idea of acquiring maps with temporal dynamics. Other studies have used public inventories and laboratory techniques such as stable isotopes, combining some of the aforementioned tools (Howard and Merrifield, 2010; Koit et al., 2021). Nonetheless, it is necessary to generate interdisciplinary geospatial methods that guarantee the effective location of both terrestrial and aquatic GDE and allow their spatio-temporal dynamics to be analyzed. Thus, the objective of this study is to develop a new geospatial method with an integrated and temporal approach for mapping potential groundwater-dependent ecosystem zones (PGDEZ). This method is the first to integrate a multicriteria approximation based on expert opinion, remote sensing-GIS techniques, and fieldwork, with a temporal approach. It is based on geospatial and conventional information, topographic parameters, multispectral indices, and climate variables. This method allows the spatio-temporal changes to PGDEZ to be mapped at an annual scale, is transferable to other arid and semi-arid environments, and is presented as a tool for sustainable GDE management amid current climate and anthropogenic changes.

2. Materials and Methods

2.1 Case study: Ligua and Petorca watersheds

The Ligua and Petorca River watersheds (32° S, 1,980 km^2 and 1,986 km^2, respectively) are located in the Valparaíso Region (central Chile) (Fig. 4.1b). The two rivers meet at the Salinas de Pullally coastal wetland (Fig. 4.1c) and their watersheds have similar hydrological, geomorphological, and climate characteristics (CNR-UDEC, 2016; Panez-Pinto et al., 2017). They present north-south-oriented sequences of geological units formed by sedimentary and volcanic rocks of the Triassic to the Pleistocene, crossed by surface channels (CNR-UDEC, 2016). In each of the valleys there is an unconfined aquifer and the entire surface of each watershed is divided into 12 hydrogeological sectors (DGA-MOP, 2014). These watersheds are characterized by a semiarid climate with a mediterranean influence, a predominantly pluvial regime, and an absence of glaciers in their Andean sections (Panez-Pinto et al., 2017). Annual precipitation varies between 253 and 319 mm, increasing toward the upper sections and concentrated in the austral winter (June, July and August) (Duran-Llacer et al., 2020). Most of the area has low humidity, clear skies, strong daily temperature fluctuations, and average annual temperatures of 14.6°C (CNR-UDEC, 2016).

The main economic activity in the area is agriculture for export, mainly of avocadoes (Panez-Pinto et al., 2017). Since 2010 there has been a moderate but long hydrological drought, which, along with major human influence (agricultural land-use change, ongoing granting of GW rights, and an inefficient water management system), has contributed to the significant decline of GW (Duran-Llacer et al., 2020).

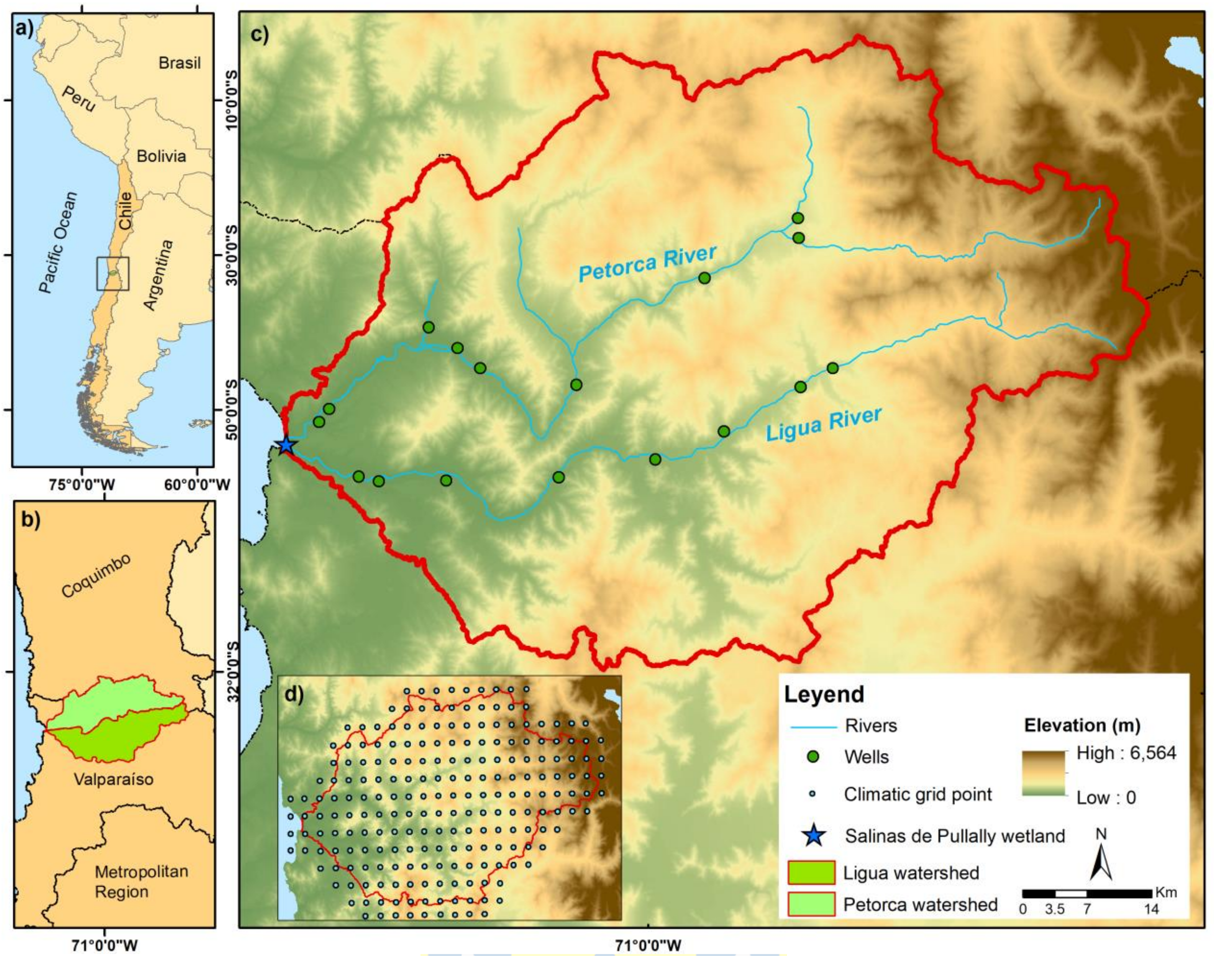

Figure 4.1 Location of the Ligua and Petorca watersheds. a) geographic context in South America; b) location in Chile; c) elevation, wells, and rivers; and d) climatic grid points (rainfall and temperature).

2.2 Methods

This section presents the proposed methodology for PGDEZ mapping. For the purposes of the study, the proposed methodology was applied for 2002 and 2017. It includes the survey process, selection and calculation of spatial parameters, assignment of weights and normalization, multicriteria assessment, validation, sensitivity analysis, and spatio-temporal analysis (Fig. 4.2).

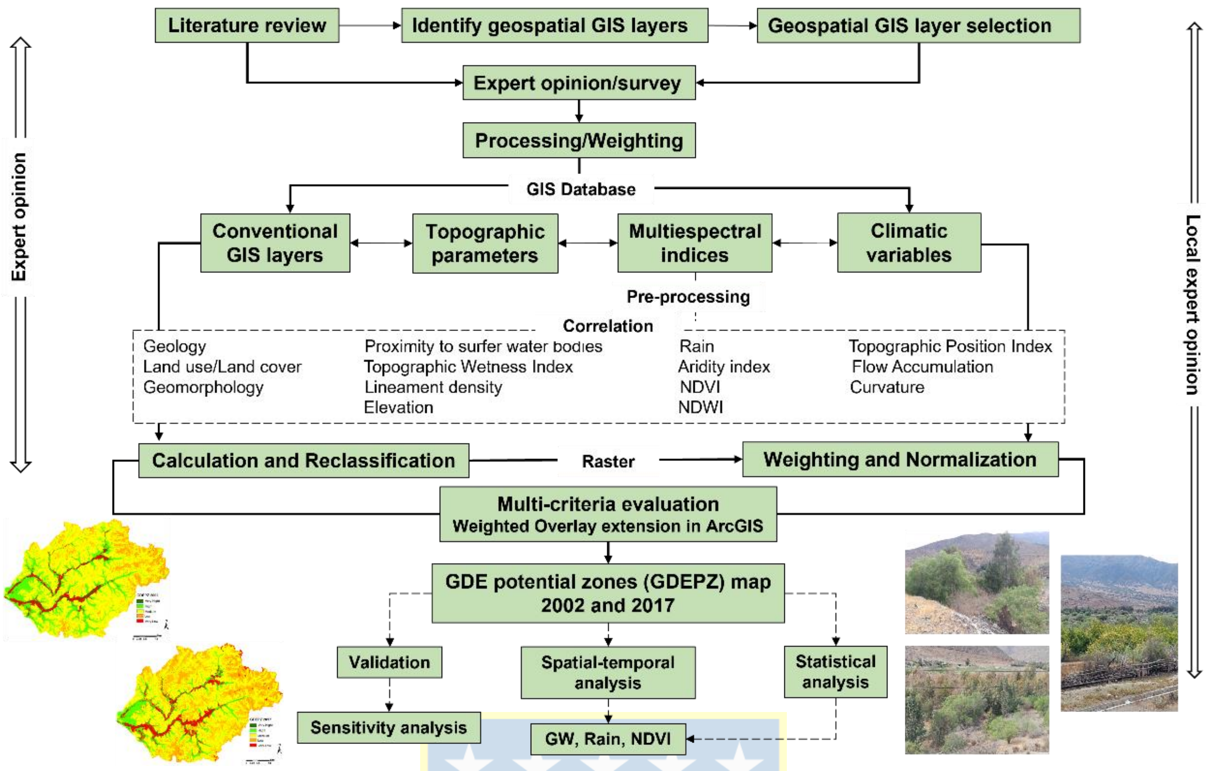

Figure 4.2 Methodological diagram

2.2.1 Literature review

An exhaustive literature review was carried out to compile all possible geospatial parameters (thematic layers) that could be predictors of the presence of GDE in arid and semi-arid environments. The reviewed publications were scientific articles and reports on mapping and analysis of GDE changes. Studies on mapping of potential GW or GW recharge zones and conceptual aspects of these ecosystems were also considered. Of the 158 publications reviewed, 51 were related to conceptualization and 74 addressed mapping and spatial analysis of GDE (Table 4.A.1 in Appendix A of this paper). Based on the analysis carried out and the actual availability of information on the study zone, all the possible geospatial parameters for GDE mapping were selected. Based on this selection, a survey of experts was conducted to assign a degree of importance to each parameter.

2.2.2 Survey and processing

A survey of various international researchers who have carried out specialized research on GDEs and mapping of potential GW zones was conducted to allow expert opinion to be taken into account. The selected researchers have broad experience in the area and have carried out high-impact studies; they work in the areas of hydrogeology, surface and groundwater hydrology, geology, ecohydrology, and geospatial technologies (GIS and remote sensing). In addition, the selection sought to include experts in both the academic and non-academic spheres, government scientists, environmental consultants, and researchers from important research centers related to the study of GDEs.

Fifty experts from 26 countries were contacted and informed about the objective of the survey and invited to participate in it. Twenty-six completed surveys were returned (The list of experts researcher is shown in Appendix 2 of this Thesis). The entire design, expert selection, and analysis process was carried out using the Delphi method (Okoli and Pawlowski, 2004). Each survey taker assigned a value from 1 to 10 to each geospatial variable according to their judgment. Expert agreement was assessed using Kendall concordance analysis (Rojas et al., 2017). This statistical test carried out SPSS software (IBM Corp. Released 2013, n.d.) gave as a result a value of $W = 0.6$, at a $p < 0.001$, which indicates that the experts applied similar standards to assign weight to the parameters (Arriagada et al., 2019).
For the analysis of the degree of importance assigned by the experts to each parameter in the survey, as well as their comprehensive comparison and selection for the study, the data were normalized by following the procedure described in Arriagada et al. (2019). Subsequently, the relative weights (W) were defined, assigning an order based on the importance of the geospatial parameters using Equation 1.

$$W = \frac{Of}{\sum Of} \quad (1)$$

where *W* is the weight based on the order; *Of* is the order as a function of the parameters and $\sum$ *Of* is the sum of all order values calculated for each parameter.

2.2.3 GIS Database

Conventional GIS layers

Geology (Gg) controls porosity and permeability, which are different for each substrate type, and also affects GW storage (Miraki et al., 2019). Geology was obtained from the national geological map (1:1000000 scale) of the National Geology and Mining Service (SERNAGEOMIN, https://www.sernageomin.cl).

Geomorphology (Gm) has a dominant role in groundwater movement and storage (Mallick et al., 2015), as it significantly impacts surface runoff and thus the occurrence, filtration, and recharge of water in the subsoil (Abijith et al., 2020). Based on fieldwork and photo interpretation of two Landsat 8 images (path/row:233/82 and 233/83, 30 x 30-m spatial resolution), a geomorphological map was created (Gumma and Pavelic, 2013). In the relief unit digitization process, the national geomorphological map (generalized scale of 1:5000000), available on the

Chilean Geospatial Data Infrastructure platform (IDE-Chile, http://www.ide.cl/), the geological map, and other thematic layers (slope and elevation) were used as foundations.

Land use land cover (LULC) affects hydrological phenomena such as infiltration, runoff, percolation and, therefore, GW (Pal et al., 2020). In addition, it provides information on the locations of human activities, vegetation, and wetlands (Mallick et al., 2019). Land-use information was acquired from Duran-Llacer et al. (2020), who obtained the data from the supervised classification of Landsat images (30-m resolution) from 2002 and 2017. Of the 19 established land-use categories, nine were regrouped in accord with the objectives of this investigation.

Topographic parameters

The greater the *elevation (E)*, the lower infiltration and recharge (Miraki et al., 2019). Low areas and depressions, especially in the flood plain region, ensure a high level of surface moisture and enrich the underground aquifer through long times of ponding (Pal et al., 2020). Elevation was obtained from the processing of four images from the ALOS PALSAR satellite (12.5-m, https://search.asf.alaska.edu/#/). Therefore, all topographic parameters were obtained at 12.5-m spatial resolution. The digital elevation model (DEM) (Fig. 1c) was used to calculate the *slope (Sp)* with the Spatial Analyst tool in ArcGIS 10.8.1 (ESRI, 2020). Slope is an important terrain characteristic that expresses the inclination of the land surface (Arulbalaji et al., 2019).

To obtain *proximity to rivers and water bodies (Prwb)* the DEM with ArcGIS tools Hydrology and Raster Calculator was used. Flow accumulation (Fa) and the drainage network were calculated (Fig. A2 in Appendix A). Bodies of water were obtained from LULC. Then the Euclidian Distance tool was applied to consider proximity, in accord with Nhu et al. (2020).

Drainage density (*Dd)* plays a crucial role in groundwater availability (Mallick et al., 2019). It is calculated as the total length of streams divided by the total area of the watershed (Ahmed and Pradhan, 2019), as shown in Equation 2, using the ArcGIS tool Line Density.

$$Dd = \frac{L}{A} \tag{2}$$

where *Dd* is drainage density, *L* is the total length of streams in km and *A*-area is the total watershed area in km^2.

Lineament density (Ld). Lineaments are linear or curvilinear characteristics that represent fault or fracture zones that result in greater secondary porosity and permeability (Arulbalaji et al., 2019). Lineaments were extracted from two cloudless Landsat 8 images (path/row:233/82 and 233/83). Preprocessing included the pan-sharpening technique with the panchromatic band and principal component analysis (PCA) in ENVI 5.3 (Environment for Visualizing Images). Next, automatic lineament extraction was carried out with the line extraction module of PCI Geomatica software (2016 version) through edge detection, threshold, and curve extraction procedures. Then in ArcGIS the lineaments were processed and filtered through visual and manual analysis, which included false-color band combinations (7,5,3) and orientation analysis using the rose diagram in Rockworks 17 software (Ahmed and Pradhan, 2019). *Ld* is defined as the relationship between total lengths of all delineated lineaments and the total area (Ahmed and Pradhan, 2019), as shown in Equation 3:

$$Ld \sum_{i=1}^{n} Li * A \quad (3)$$

where *Ld* is lineament density, *Li* total lineament length, and *A* is the area.

The *topographic wetness index (TWI)* is based on the idea that a terrain profile controls the distribution of water and the areas prone to water accumulation (Qadir et al., 2020). The *TWI* is calculated using Equation 4:

$$TWI = ln(\alpha / tan\beta) \quad (4)$$

where α is the contributing upslope area and β is the topographic gradient.

The *topographic position index (TPI)* is a widely used algorithm for measuring topographic slope and automating landform classifications (Arulbalaji et al., 2019) and has been used in the location of GDEs (Münch and Conrad, 2007). Equation 5, below, was used to calculate this index.

$$TPI = Mo \sum_{n-1} Mn/n \quad (5)$$

where *Mo* is the elevation of the model point under evaluation, *Mn* is the elevation of the grid and *n* is the number of surrounding points employed in the evaluation.

Flow accumulation (Fa) represents water movement on the surface. Flow direction per cell is calculated first and then the cumulative flow. This technique is generally used to delineate stream networks (Münch and Conrad, 2007). It is calculated using the Spatial Analysis tool, like *curvature (Ct)* and the *terrain roughness index (TRI).* Curvature is a quantitative expression of the nature of the surface profile and can be concave or convex. The *TRI* expresses the difference between adjacent cells of a DEM and generally expresses the undulation of the topography (Arulbalaji et al., 2019). For greater detail, consult Riley et al. (1999).

Multispectral indices

The *normalized difference vegetation index (NDVI)* is the ratio of the difference in the spectral reflectance of the near-infrared band (NIR) and the red band (R) (Ahmed and Pradhan, 2019), as seen in Equation 6.

$$NDVI = \frac{NIR-R}{NIR+R} \tag{6}$$

It has been demonstrated that the *NDVI* surpasses other indices at quantifying normally scarce vegetation in arid environments (Huntington et al., 2016), and it has been used in various studies to identify terrestrial ecosystems and wetlands that depend on GW, according to the principle that ecosystems that maintain a constant amount of green vegetation are defined as GDEs (Barron et al., 2014; Doody et al., 2019, 2017). With this criterion, Landsat images of the dry season were used to calculate all the spectral indices. According to Duran-Llacer et al. (2020), in the winter-spring of 2002 the greatest cumulative rainfall occurred and the summer of 2003 was the season with the greatest GW level in recent decades. Therefore, in the mapping process images from the 2002-2003 and 2016-2017 summers (December-January-February) were used. Four Landsat images (30-m spatial resolution) with a low cloud percentage (2 ETM+ del 2003 y 2 OLI del 2017) obtained from the site https://earthexplorer.usgs.gov/ were used. The preprocessing included geometric, topography, radiometric, and atmospheric correction, in accord with the methodologies employed in Duran-Llacer et al. (2020).

The *normalized difference wetness index (NDWI)* is very sensitive to canopy water content (Marques et al., 2019) and allows vegetation moisture conditions to be monitored (Barron et al., 2014). It is calculated using the reflection of near-infrared (NIR) and short-wave infrared (SWIR), according to Equation 7:

$$NDWI = \frac{NIR-SWIR}{NIR+SWIR} \tag{7}$$

The *enhanced vegetation index (EVI)* is similar to the *NDVI* and can be used to quantify the greenness of vegetation. However, the *EVI* corrects for some atmospheric conditions and background canopy noise and is more sensitive in areas with dense vegetation (Huete et al., 2002). Therefore, it has been widely used to map GDE (Liu et al., 2021). It was calculated with Equation 8:

$$EVI = G * ((NIR - R)/(NIR + C1 * R - C2 * B + L) \tag{8}$$

where *G* is the gain factor (*G*=2.5), *C1* and *C2* are the aerosol resistance term coefficients (*C*1=6, *C*2=7.5), *B* is the blue band, and *L* is the canopy background adjustment (*L*=1).

Climate variables

The distribution and intensity of *rainfall (R)* directly affect the infiltration of runoff water and control the recharge volume (Pal et al., 2020). The monthly gridded precipitation product CR2MET 0.05° (CR2, http://www.cr2.cl/) and the recovered information per pixel were used to calculate annual rainfall in 2002-2003 and 2016-2017, taking into account the hydrological year in Chile (Abril, 1st to March, 31) (Alvarez-Garreton et al., 2018). Its spatial distribution was obtained using the ordinary Kriging interpolation method, which was also used to map the *aridity index (Ai)*. The UNEP Aridity index (United Nations Environmental Programme, 1992) provides information related to evapotranspiration processes and the rainfall deficit for potential vegetative growth (Marques et al., 2019). In the calculation of *Ai*, minimum and maximum temperature data from CR2MET (≈5-km) were processed to obtain potential evapotranspiration (PET), in accord with the Hargreaves method (Hargreaves and Samani, 1985), and it was calculated using the SPEI package (Beguería and Vicente-Serrano, 2017) in the Rstudio program. *Ai* is expressed in the following form:

$$Ai = \frac{R}{PET} \qquad (9)$$

where *Ai* is the aridity index, *R* is precipitation, and *PET* is potential evapotranspiration.

2.2.4 Final variable selection

To eliminate possible collinearity between variables and information duplication, a Pearson correlation analysis of the 18 variables initially considered for GDE mapping was carried out. First, they were converted to raster format and then resampled at the same spatial resolution and reprojected on the same coordinate system (30x30-m, WGS-84 19S). The correlation was carried out with the ArcGIS Multivariate tool. The parameters with correlations greater than 0.5 (moderate to strong correlations) were considered for elimination from the final model. Subsequently, those with the lowest degree of assigned importance according to the surveys were eliminated, leaving 14 variables that presented the least correlation with each other (Table 4.1).

2.2.5 Multi-criteria evaluation

The ranges of each geospatial parameter were reclassified and normalized to establish its degree of importance or probability of locating a GDE that it indicates. The proposed classes in each parameter were determined based on local expert opinion and the consulted bibliographic sources, with each assigned a ranking of 1 to 5 (Münch and Conrad, 2007). The classes establish the degree of probability of PGDEZ presence. Those considered inadmissible for locating a GDE were considered as separate classes, placing them in the category of “not applicable.” The scale used was the following: Very High, High, Medium, Low, and Very Low, in accord with Gou et al. (2015). The range and references of each reclassified geospatial parameter are presented in Table 4.1. The reclassification and normalization of the variables not considered in the final model are shown in Table 4.A.2 of Appendix A (This paper).

Table 4.1. Range and weight of each geospatial variable reclassified according to the probability of the presence of PGDEZ.

Parameter	Weight (%)	Scale or Potential	Class	Rank	References
Gg	11.7	Very High Very High High Medium Low Very Low	Sedimentary sequences Marine-littoral sedimentary sequences Volcanic-sedimentary-marine sequences Continental volcanic-sedimentary sequences Volcanic sequences Intrusive rocks	5 5 4 3 2 1	(CNR-UDEC, 2016; CNR, 2013) (Dresel et al., 2011; Kuginis et al., 2016)
R	11.1	Very High Hight Medium Low Very low	< 320 320-380 380-420 420-450 >450	5 4 3 2 1	(Hoyos et al., 2015; Marques et al., 2019)
LULC	10.5	Very High Very High Very High High High Medium Very low No Apply No Apply	Scrublands and grasslands Exotic plantations Water bodies Bare soil Espinos Native forest Rocks Reservoirs and urban areas Agricultural land	5 5 5 4 4 3 2 - -	(Doody et al., 2019, 2017; P. E. Dresel et al., 2010; Gou et al., 2015b; Huntington et al., 2016; Münch and Conrad, 2007)
Gm	9.9	Very High Very High Very High High High Medium Medium Low Very Low Very low	Transverse valleys with fluvio-alluvial deposits Natural water bodies Medium-order streams Low and midland transverse pre-cordillera valleys Low-order streams Coastal plain with fluvio-marine deposits Andean pre-cordillera valleys Transverse ridges Dunes and beaches Andes Mountains	5 5 5 4 4 3 3 2 1 1	(Arulbalaji et al., 2019; Gou et al., 2015b; Serov et al., 2012)
NDVI	9.3	Very High High Medium Low Very low	0.6-1 0.35-0.6 0.1-0.35 0-0.1 -1-0	5 4 3 2 1	(Barron et al., 2014; Eamus et al., 2016; Huntington et al., 2016)
Prwb	8.1	Very High High Medium Low Very low	0-200 200-400 400-600 600-800 > 800	5 4 3 2 1	Local expert opinion (Mallick et al., 2015; Serov and Kuginis,

					2017)
Parameter	**Weight (%)**	**Scale or Potential**	**Class**	**Rank**	**References**
TWI	7	Very High High Medium Low Very low	12-25.8 7-12 5-7 3-5 0.5-3	5 4 3 2 1	Local expert opinion (Arulbalaji et al., 2019)
NDWI	6.4	Very High High Medium Low Very low	0.4-1 0.15-0.4 0-0.15 -0.15-0 -1- -0.15	5 4 3 2 1	Local expert opinion (Barron et al., 2014)
Ld	5.8	Very High High Medium Low Very low	2-3.6 2-2.5 1-2 0.5-1 0-0.5	5 4 3 2 1	(Münch and Conrad, 2007; Tiwari and Kushwaha, 2020)
E	5.2	Very High High Medium Low Very low	< 800 800-1,600 1,600-2,400 2,400-3,200 >3,200	5 4 3 2 1	Local expert opinion
Ai	4.6	Very High High Medium Low Very low	0.3-0.5 0.5 -0.6 0.6 - 0.68 0.68 - 0.75 > 0.75	5 4 3 2 1	(Hoyos et al., 2015; Marques et al., 2019)
Fa	4	Very High High Medium Low Very low	20-100 100-5,000 5,000-10,000 5-20 0-5	5 4 3 2 1	Local expert opinion (Münch and Conrad, 2007)
TPI	3.5	Very High High Medium Low Very low	-1.87-7.58 -7.58- -1.87 -141 -7.58 7.58-24.24 24.14-110	5 4 3 2 1	(Arulbalaji et al., 2019; Münch and Conrad, 2007)
Ct	2.3	Very High High Medium Low Very Low	< -1.5 -1.5- 0.1 0.1-1.5 1.5-3 > 3	5 4 3 2 1	Local expert opinion (Dar et al., 2010)

Gg = Geology, R = Rain, LULC = Land use land cover, Gm = Geomorphology, NDVI = Normalized Difference Vegetation Index, Prwb = Proximity to rivers and water bodies, TWI = Topographic wetness index, NDWI = Normalized Difference Wetness Index, Ld = Lineament density, E = Elevation, Ai = Aridity index, Fa = Flow accumulation, TPI = Topographic position index, Ct = Curvature.

2.2.6 Mapping of PGDEZ

To map PGDEZ, the GIS-based multicriteria weighted overlay method (Arulbalaji et al., 2019) was used in ArcGIS, with the Spatial Analysis tool, following Equation 10:

$$PGDEZ = (F1 * W1) + (F2 * W2) + \ldots (Fi * Wi) \qquad (10)$$

where *PGDEZ* is the potential groundwater-dependent ecosystem zone; *Fi* are the ranges of each reclassified parameter, and *Wi* is the relative score by influence weight.

The final PGDEZ map at 30-m resolution was classified into very high, high, moderate, low, and very low zones after reclassifying the “not applicable” category as very low.

2.2.7 Validation and sensitivity analysis

The validation was carried by first selecting 100 random points classified as high or very high (end of summer season) for subsequent visits and validation of the results in the field. The field survey was carried out using a GPS (global positioning system) and each georeferenced point was transferred to a GIS.

Sensitivity analyses are used to identify the model inputs that have a significant impact on the result (Marques et al., 2019). The sensitivity analysis was carried out by omitting only the individual parameters of a temporal nature (LULC, Rain, NDVI, NDWI and Ai) used in the multicriteria analysis to identify the sensitivity or importance of each parameter in the types of PGDEZ and that which most influenced the changes between 2002 and 2017. For more details on sensitivity analysis, see Mandal et al. (2016).

2.2.8 Spatio-temporal analysis of PGDEZ

To analyze the spatial and temporal changes in PGDEZ the surface areas in 2002 and 2017 were compared. Next, only areas with very high GDE potential in both years were selected to obtain GDE polygons and analyze their spatio-temporal dynamics amid GW-level changes in the watersheds (Duran-Llacer et al., 2020). In this analysis the NDVI was used as a proxy for GDE condition. Each polygon was delimited in accord with the following criteria: 1) proximity of 1.5 km to available observation wells, 2) coincidence with the control points visited to validate the results in the field, 3) location in a common hydrogeological sector, 4) same height of well and polygon, and 5) covered by more than half of each Landsat pixel, in order to avoid the edge effect. Some of these criteria were taken and modified from Klausmeyer et al. (2019). Finally, 17 GDE polygons corresponding to 17 wells were obtained. The maximum water table depth did not exceed 20 m, confirming that the unconfined aquifers were shallow and fulfilled the conditions necessary for adequate GDE health and location (Klausmeyer et al., 2019). The well data were obtained from the General Water Directorate of Chile (DGA, https://snia.mop.gob.cl/BNAConsultas/reportes).

An NDVI time series from 2001 to 2017 was obtained after processing Landsat images in Google Earth Engine (GEE). GEE is a programming platform offered by Google for rapid analysis of satellite information (Gorelick et al., 2017). The Surface

Reflectance product of all the Landsat images (5 TM, 7 ETM+SLC, and 8 OLI) was used. The images were processed to mask clouds and shadows using the CFmask product (Zhang et al., 2021). Then the image collections were merged, the average NDVI was calculated, and this result was clipped using only the vector data of the studied polygons. Subsequently, the NDVI of each dry season (December-January-February) of each GDE polygon was averaged.

The CR2MET monthly rainfall satellite data were used to calculate the cumulative totals per hydrological year (April 1st to March 31). With the average summer NDVI values, the yearly rainfall totals, and the annual GW level average, the response of GDEs to changing groundwater levels was analyzed in accord with Huntington et al. (2016) and Klausmeyer et al. (2019). To evaluate the degree of influence of GW and rainfall amid changes in GDE, a Pearson correlation and a linear regression were carried out (Liu et al., 2021). In addition, a trend analysis, trend, and change-point analysis of the NDVI time series were carried out using Mann Kendall (Kendall, 1975; Mann, 1945), Sen's slope (Sen, 1968), and Pettitt tests (Pettitt, 1979).

3. Results and Discussion

3.1 Variables selected for the final model

The results of the Pearson correlation are shown in Fig. 4.A.1 of Appendix A of this Thesis. The *EVI* (Fig. 4.A.2) presented high and moderate correlations with *LULC* and the *NDVI* in both years (r > -0.51 and -0.55, r > 0.76 and 0.92, respectively); therefore, it was not considered. *Dd* (Fig. A.2) presented correlations greater than 0.5 with geomorphology, elevation, and proximity to rivers, and was also discarded from the final model. The other variables not used in the multicriteria model were slope and the roughness index *TRI* (r > 0.52 and r > 0.51, respectively). The Pearson coefficients between the aridity index and elevation were 0.65 and 0.67; however, neither was eliminated, as they are variables with a different relationship to GDEs. Elevation influences GW recharge and infiltration, while the aridity index responds to vegetative growth potential.

3.2 Conventional GIS layers

The *geology* (Fig. 4.3) was regrouped into 5 classes according to substrate type (Table 4.1) and capacity to favor interactions among groundwater, surface water and terrestrial vegetation. The geological units follow a north-south pattern and are formed mainly by sedimentary and volcanic rocks. The valleys are shaped by alluvial, colluvial, and fluvial deposits of fine to medium sand, gravel, and silts, generating a high degree of interaction between surface water and groundwater (CNR-UDEC, 2016). The marine-littoral sedimentary sequences are located in the lower parts of the watersheds and are made up of rocks such as lavas, calcareous sandstones, lutites, limestones, and conglomerates. In much of the watersheds, continental volcanic-sedimentary sequences are present, formed by epiclastic and pyroclastic rocks, stromatolitic limestones, and lavas. The intrusive and volcanic rocks sequences were assigned ranks of 1 and 2 in the potential for GDE zones (Table 4.1), which are characterized by granodiorite, gabbro, lava, breccia, and andesitic-basaltic pyroclastic rocks.

The *geomorphology* of the area is characterized by the valleys of rivers that pass through transverse ridges, coastal plains, and the Andes Mountains. The geomorphological map was created in greater detail in accord with the objectives of this study, and 11 geomorphological units were obtained. The dune and beach zones were considered to be of low potential for GDE zones, as were the Andes Mountains and transverse ridges, which account for the greatest portion of the territory. The main valleys are known as transverse valleys with fluvio-alluvial deposits, which present the greatest probability of PGDEZs due to their substrate characteristics and the high degree of interaction between surface water and groundwater. Natural water bodies were also classified as having high potential. Low and midland transverse pre-cordillera valleys are the small valleys found between the transverse ridges and are connected to the main valleys (Fig. 4.3). Andes pre-cordillera valleys are small intermountain valleys of the high or Andean zone, which were assigned medium potential.

LULC was reclassified into 9 categories to represent GDE potential in 2002 and 2017. Grasslands and scrublands were assigned a very high potential, as they are found in zones near valleys with the presence of sclerophyllous arborescent bushes. The native forest of this classification is dominated by sclerophyllous vegetation located in the middle and upper zones of the watersheds. Rocks are classified as a type of bare soil in the land-use categories; however, here rocks were classified as separate category, as the bare soil in this study includes river channels and other land without vegetation near riparian zones that are considered to be of high potential for location of a GDE. Therefore, rocks were assigned a rank of 2; they are present in the cordillera zone (Table 4.1 and Fig. 4.3). GDE mapping generally excludes most agricultural land and landscapes dominated by human activity (Klausmeyer et al., 2018); therefore, farmland, reservoirs and urban areas were considered an excluded class (not applicable) in the weighted overlay model. Forestry plantations were not excluded, as the trees can be phreatophytes and draw on GW (Dresel et al., 2010). The espino is a type of thorny bush present in the lower parts of the watersheds near valleys and in middle areas toward hills or transverse ridges. Natural water bodies such as rivers, estuaries, and lakes were assigned the rank of “very high.”

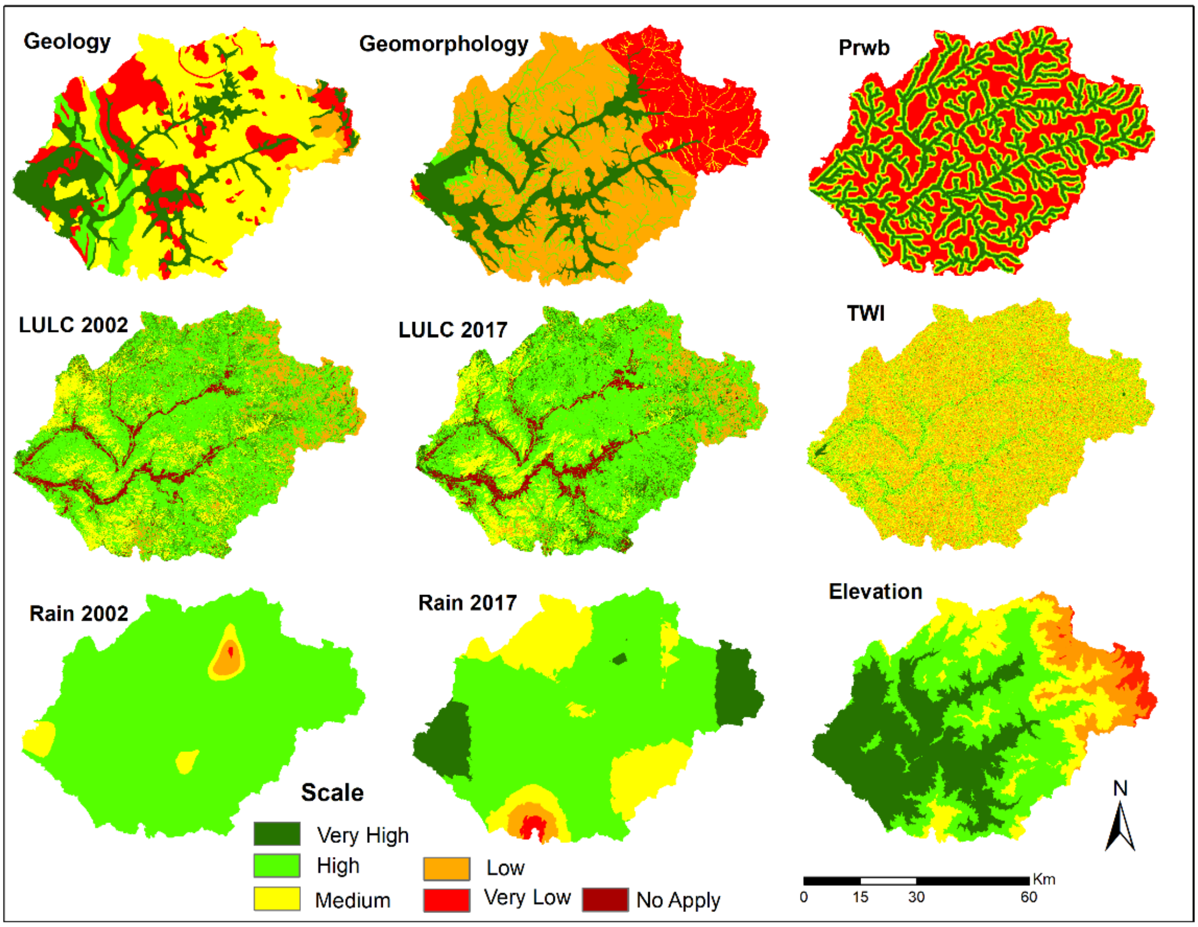

Figure 4.3. Geospatial parameters used in the PGDEZ mapping.

3.3 Topographic parameters

Elevation (Fig. 4.3) was grouped into five classes. The first class covers heights of up to 800 m; it is considered to have high potential for GDE zones and is characteristic of flat and gently sloped areas. Potential can be high between 800 m and 1,600 m, but at greater terrain elevations potential decreases (Table 4.1). The pre-cordillera zone is found above 2,400 m, where there is a low probability of finding GDE zones.

High *proximity to rivers and water bodies* (*Prwb*) indicates a high probability of finding GDE (Nhu et al., 2020). Rivers, streams, or baseflow in river systems and adjacent aquatic and riparian ecosystems can be classified as GDEs (Eamus et al., 2016). These ecosystems depend on the baseflow of GW, especially during dry seasons in seasonally dry climates or permanently dry climates in arid zones (Murray et al., 2003). The probability is the highest at a distance of up to 200 m, which is characteristic of the main valley zones and small intermountain valleys. There is a high probability in the 200-400-m range and a medium probability in the 400-600-m range. Distances greater than 800 m are found in the highest zones of the study area (Fig. 4.3).

The *Topographic Wetness Index* (Fig. 4.3) reflects the potential groundwater infiltration caused by topographic effects (Arulbalaji et al., 2019) and manifests soil moisture conditions (Nhu et al., 2020). It was regrouped into five classes and ranged from 0.5 to 25.8 (Table 4.1). High weights were assigned to high TWI values and vice versa. The highest values are observed near the coastal plain and Salinas de Pullally coastal wetland, at the confluence of the Ligua and Petorca rivers (Duran-Llacer et al., 2020), as well as in the transverse valleys.

Lineament density (Fig. 4.4) was reclassified into five categories and the highest weights were assigned to the greatest lineament densities. The values ranged from 0 to 3.6 km/km^2. The lowest weight was assigned to values between 0 and 0.5 km/km^2 and the highest to values between 2 and 3.6 km/km^2 (Table 4.1). Lineaments and fracture zones are used to analyze fractured aquifer potential and are therefore associated with the presence of GDEs (Münch and Conrad, 2007). Lineaments are showed in Appendix 3 of this Thesis.

The *topographic position index* (Fig. 4.4). Many relief forms such as plains, hilltops, and valley bottoms are correlated with the *TPI*. Values near 0 indicate a flat surface (Arulbalaji et al., 2019). The range in the study area was between -141 and 110. The highest weights were assigned to low *TPI* values and vice versa (Arulbalaji et al., 2019).

Flow accumulation (*FA*). In the study area potential zones classified as “high” and “very high” varied between 20 and 5,000 (no. of cells), with some areas near the confluence of the rivers standing out (Fig. 4.4). The lowest potential is presented by areas with values 20 (0-5 “very low” and 5-20 “low”). The *FA* technique allows cells with high flow accumulation (stream channels) to be extracted, but in this study the cells that make up the entire accumulation surface are also of great interest, as they could be interpreted as wet areas and therefore areas with potential for a GDE (Münch and Conrad, 2007).

Curvature (Fig. 4.4). Water tends to decelerate in a convex profile and accumulate in a concave profile, which can be obtained upon calculation of *curvature* (Fig. 4.3). In the study area negative values are assigned ranks of “high” and “very high,” as they represent concave zones, while positive values indicate a convex surface and thus a low probability of finding GDE. A value of zero indicates that the surface is flat (Dar et al., 2010).

3.4 Multispectral indices

The *NDVI* is a reliable indicator of vegetation density and vigor (Barron et al., 2014). Values between 0 and 1 indicate the presence of vegetation, with 1 being the greatest possible green vegetation density (Pal et al., 2020). The *NDVIs* of the dry seasons of 2002-2003 and 2016-2017 were reclassified and categorized into five classes. A high weight was assigned to values near 1 and vice versa (Table 4.1). In 2002 the values oscillated mostly between 0.1 and 1, while in 2017 the *NDVI* decreased, with values that oscillated between -0.5 and 0.35 in most of the area, reflecting unfavorable conditions for finding a GDE (Fig. 4.4). The decrease in vegetation greenness in the period is a possible consequence of the significant GW depletion and the megadrought that have affected this region of Chile (Duran-Llacer et al., 2020; Garreaud et al., 2019).

The *NDWI* has been used to associate moisture conditions with GDEs, making it useful in GDE mapping (Barron et al., 2014; Doody et al., 2017). *NDWI* values varied between -1 and 1. The wettest conditions were presented in the valleys and other zones with dense vegetation, with values above 0.15 (high and very high potential), while most of the area presented values below 0. As the region has semiarid conditions, these low *NDWI* values are expected; however, a decrease in the index was observed in the studied period (Fig. 4.4).

3.5 Climate variables

Rainfall (*R*) and the *aridity index* (*Ai*). The lowest values of each of these climate indices were assigned to the “high” and “very high” potential classes, and vice versa for high values. For rainfall in 2002-2003 (Fig. 4.3), cumulative annual totals exceeded 450 mm in almost the entire study area, while in 2016-2017 the greatest spatial distribution was presented by totals between 320 and 380 mm, with totals even below 320 mm in the coastal and cordillera zones. In Hoyos et al. (2015) and Marques et al. (2019) it is posited that in a wetter climate, in which ecosystem needs are met through precipitation, there is a low probability of the ecosystems depending on GW; therefore, the more rainfall, the lower the probability of GDE presence.

Ai values in the middle and lower areas oscillated between 0.3 and 0.5 (very high potential); due to its degree of aridity, the climate is classified as semiarid in accord with UNEP, (1992). Values between 0.5 and 0.6 were assigned high potential and values between 0.6 and 0.68 (subhumid dry climate) were deemed to indicate medium potential. In the pre-cordillera zone, the values were above 0.68 (wet and hyper-wet conditions), indicating low and very low potential (Table 4.1 and Fig. 4.4). A decrease in values in some zones was also observed, which indicates an increase in aridity in the studied period.

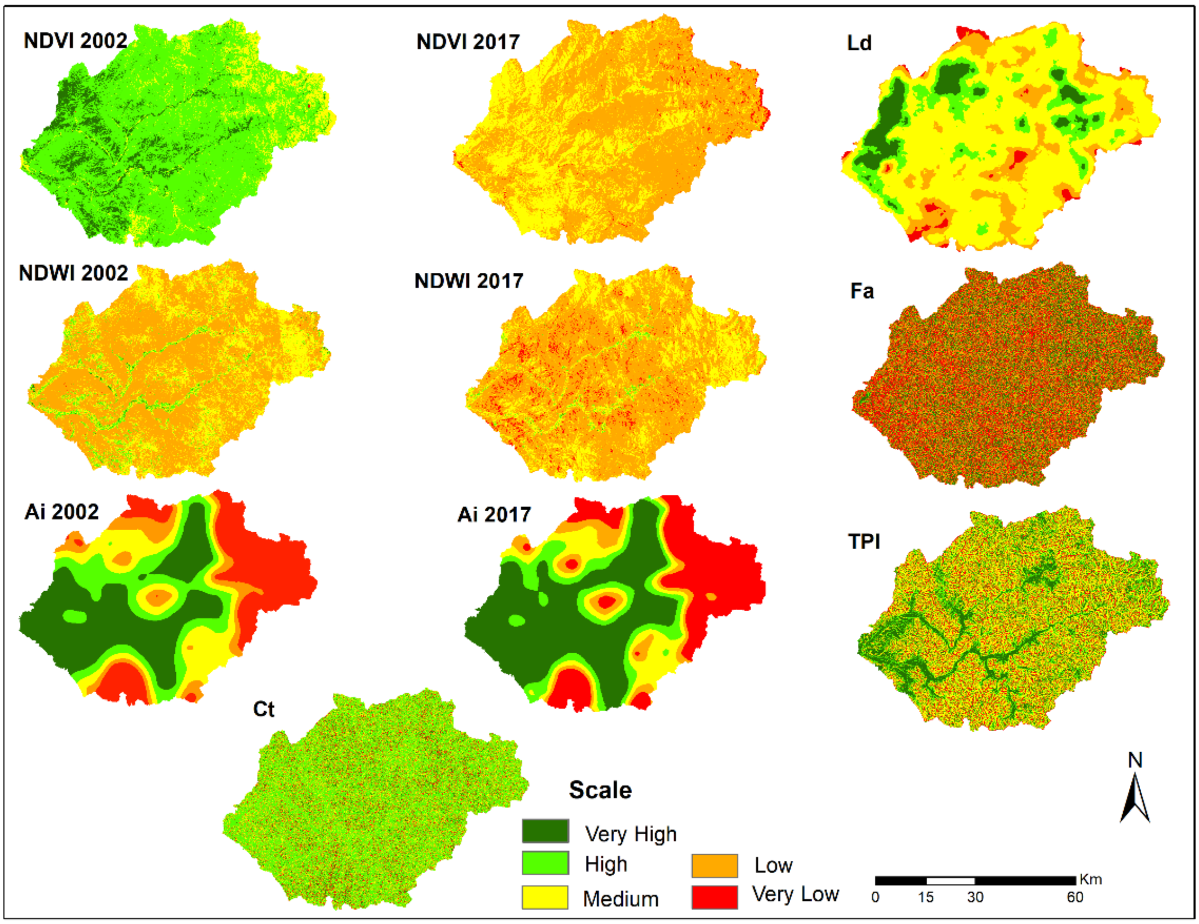

Figure 4.4. Geospatial parameters used in the PGDEZ mapping.

3.6 Potential Groundwater-Dependent Ecosystem Zones (PGDEZ) in 2002-2017

The PGDEZ maps of the Ligua and Petorca watersheds (Fig. 4.5) reveal five classes or zones (very high, high, medium, low, and very low) that represent the potential of locating GDEs. The "very high" zone was found mainly in the river valleys, flat zones where there is significant interaction between surface water and groundwater. It was also located in the vicinity of the Salinas de Pullally estuary or coastal wetland. The "high" zone presented the same spatial distribution as the "very high" zone, but with a greater area and a presence in other places with intermountain valleys in both watersheds. It was characterized by flat terrain, greater soil moisture, denser vegetation, sedimentary rocks, and a higher degree of aridity, these two classes represent the greatest probability of finding GDEs in the study area, both aquatic and terrestrial systems such as rivers, riparian vegetation, grasslands, trees, bushes, springs, wetlands, and estuarian ecosystems. The "medium" zone comprised small valleys in more elevated areas and a portion of the transverse ridges. The "low" zone consisted of the transverse ridges and more elevated parts of the watersheds, while the "very low" zone was made up mostly of the farmland that extends though the main valleys (near rivers and GDEs), although steeply sloped areas in the pre-cordillera zone, reservoirs, and built-up areas are also characteristic of this zone.

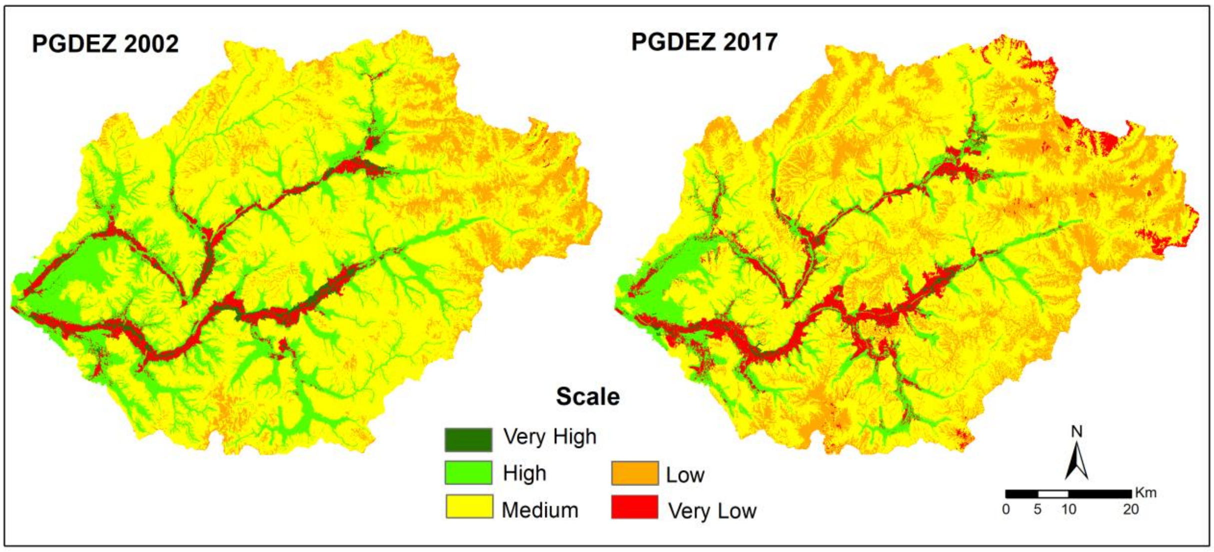

Figure 4.5. Maps of PGDEZ in 2002-2017.

Regarding the temporal evolution, it was observed that the “very high” class area decreased by 2,816 ha between 2002 and 2017 and accounted for 1.36 % and 0.64 % of the total, respectively. The “high” zone (20.04 % and 12.61 %) lost an area of 29,072 ha, making it the most affected or greatest loser of surface area (Fig. 4.5 and Table 4.2). The “medium” class has the greatest surface area (62.6 % and 58.0 %). Meanwhile, the “low” and “very low” classes increased, with “low” undergoing a greater increase (41,389 ha or 10.58 %). The “very low” class increased by 10,157 ha, mainly as a result of farmland expansion.

The changes in the two watersheds were different. The areas of the “very high” zones decreased slightly more in the Petorca watershed (0.03 %), while the greatest decreases and increases of the remaining categories occurred in the Ligua watershed, as in the case of the “low” class (3.13 % greater than the change in the Petorca watershed). This is a result of the greater increase in farmland and sharper reduction of GW in the Ligua watershed (Duran-Llacer et al., 2020).

Table 4.2. PGDEZ in 2002 and 2017 by category.

PGDEZ	Surface (ha)		Change (ha)	Surface (%)		Change (%)
	2002	2017		2002	2017	
Very High	5,332	2,516	-2,816	1.36	0.64	-0.72
High	78,379	49,306	-29,073	20.04	12.61	-7.43
Medium	244,725	227,110	-17,615	62.58	58.08	-4.50
Low	39,106	80,495	41,389	10.00	20.59	10.58
Very low	23,491	31,605	10,157	6.01	8.08	2.08

3.6 Validation

During the field validation (end of summer season), it was possible to confirm that 100% of the 100 visited points (“high and “very high” zones) manifested GDE presence. Vegetation in good health or with a green color indicated GW input in different zones. In addition, some types of deep-rooted trees and bushes (phreatophytes) located along a natural moisture gradient indicated the location of a GDE. At 10 of the visited points evident deterioration in vegetation health and vigor was observed, reflecting the ecohydrological response of these ecosystems to hydroclimatic and anthropogenic changes. Some photographs taken at the 14 selected points are shown in Fig. 4.6.

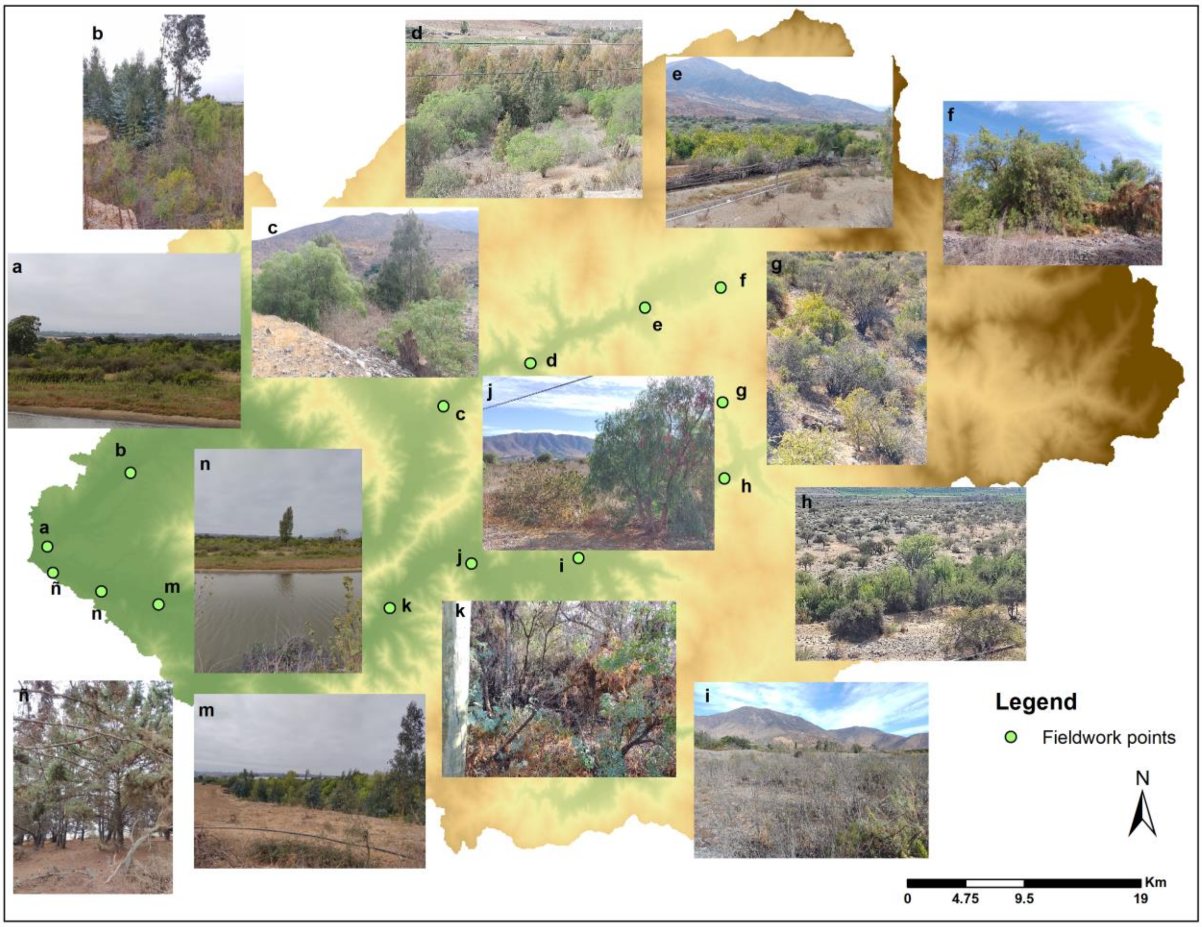

Figure 4.6. Some photographs taken by the authors at the points selected for validation visits; (a-f) in the Petorca watershed and (g-ñ) in the Ligua watershed.

3.7 Sensitivity analysis

After excluding each parameter of a temporal nature, it was possible to confirm which one had the greatest influence on or sensitivity to changes in the percentage of the area of each zone classified according to GDE potential. In addition, that with the greatest influence on the changes that occurred between 2002 and 2017 was calculated; the results are shown in Table 4.A.3 of Appendix A of this paper.

The exclusion of rainfall increased the “very high” and “high” zones in 2002 (by 2.16 % and 5.50 %, respectively), while *LULC* was the most significant for the remaining zones. In 2017 the “very high” zone was the most sensitive to the *NDVI* (0.91 %) and *LULC* remained the most important variable in changes in the other categories, contributing the greatest increase or decrease in “low” and “very low” zones (11.56 % and 7.80 %, respectively). In terms of total change between 2002 and 2017 expressed as a percentage, rainfall proved to be the variable with the greatest influence on PGDEZs (“very high” and “high”). However, the “medium” and “low” categories were more affected by the *NDVI* and the “very low” zone by the exclusion of *LULC*.

3.8 Assessment of spatio-temporal changes in PGDEZs

Fig. 4.7 shows the temporal dynamics of the summer NDVI in 12 of the 17 identified GDE polygons, as well as the behavior of GW levels and rainfall associated with each ecosystem. The behavior of the remaining five GDE polygons (1, 4, 9, 10 and 14) is shown in Fig. 4.A.3. A generalized decrease in the NDVI is observed, coinciding with the decrease in rainfall and GW. The reduction is sharper from 2010 to the summer of 2015 and 2016, showing the relationship among the variables. This period coincides with the so-called megadrought that has affected Chile (Garreaud et al., 2019) and these watersheds in particular (Duran-Llacer et al., 2020). However, in a few cases the NDVI time series is not consistent with GW behavior in years prior to 2010, which indicates that there are other factors that influenced the NDVI such as land-use changes. Indeed, land use changed in this period, determining a variation in the NDVI as a result of irrigation activity in the agricultural areas near these GDEs. The NDVI values generally oscillated between 0.30 and 0.59. In some cases, the decrease was sharper such as at GDE 10 (0.28 in summer 2013-2014), located in the Ligua watershed; however, the general decrease in the NDVI was approximately 0.1.

Both rainfall and GW are related to vegetation vigor (Huntington et al., 2016), which the results confirm. The significant decrease in GW in these watersheds was mostly influenced by human activity according to Duran-Llacer et al. (2020), and the NDVI trend analysis showed a statistically significant decrease in 14 (82.3%) of the 17 GDE polygons (p-value < 0.05, 95% confidence). Meanwhile, points with significant changes in between 2009 and 2011 were found in 16 GDEs (94%), with the greatest number of significant change points in 2010 (50% of the 16). Analysis of the results of the correlation and linear regression between NDVI-GW and NDVI-R showed that 15 GDE polygons (88 %) presented a stronger NDVI-GW relationship, demonstrating that the GDEs were affected more by the decrease in GW than by the decrease in rainfall and that the proposed method indeed serves as a tool for PGDEZ mapping. In three cases the statistical indicators were low, which could be a consequence of nearby agricultural zones and rainfall. Nonetheless, in most of the polygons the statistical indicators were consistent and showed the close relationship between the

GDEs and GW (r Pearson ≥ 0.74, y R^2 ≥ 0.54). These results are shown in Table 4.A.4. It is important to stress that depth to groundwater before 2010 did not exceed 10 m, which is within the threshold for dependent vegetation to access GW according to D. Eamus et al. (2015) and Rohde et al. (2019); this is another form of validation of the method. After 2010, the water table level decreased, resulting in the reduction and degradation of the GDEs. This ecohydrological response to aquifer depletion entails changes in productivity, biodiversity, and ecosystem services, as stated in OGIA (2019).

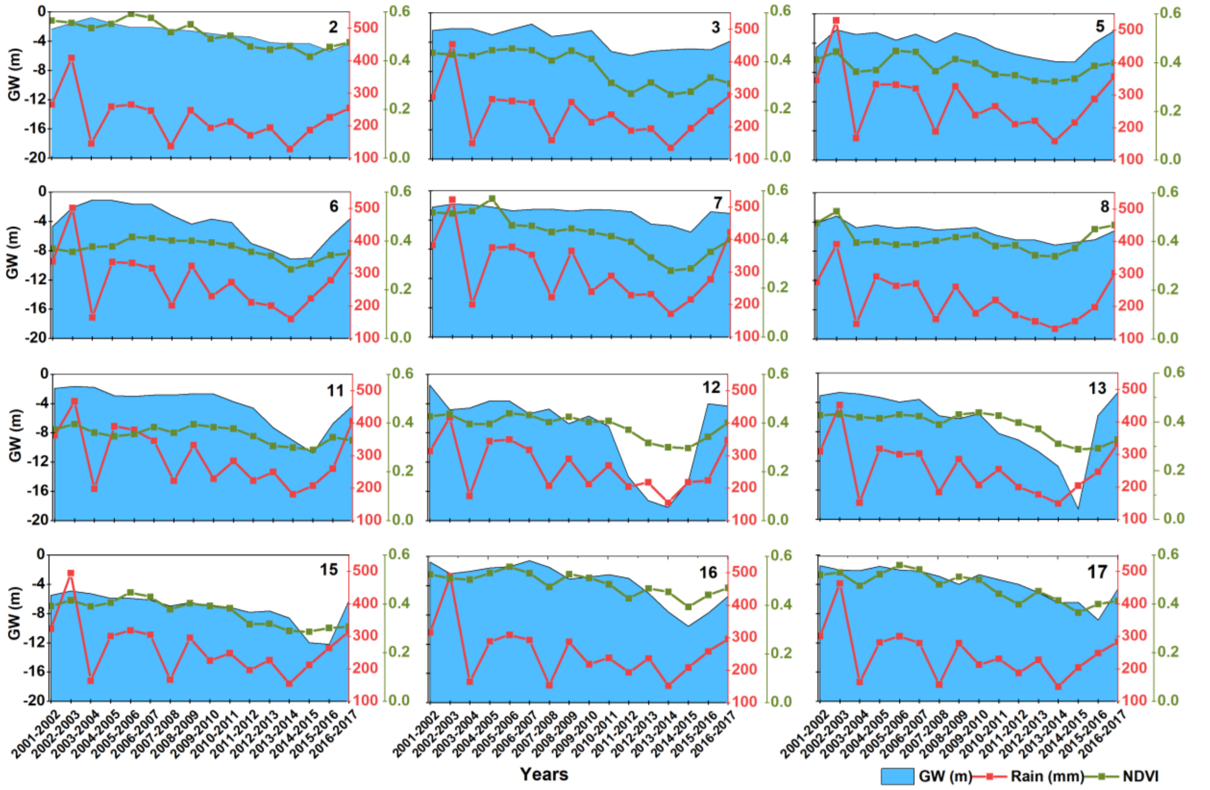

Figure 4.7. Time series of average summer NDVI, average annual GW, and annual R by PGDEZ polygon. 2) to 8) in the Petorca watershed and 11) to 17) in the Ligua watershed.

3.9 Considerations and limitations

The proposed methodology is applicable to other arid and semiarid regions, but information quality and quantity must be taken into account. To obtain a new method of analysis on an annual scale of the spatio-temporal changes of the GDEs was a great achievement of this research. The integral approach achieved through the use of different geospatial parameters such as conventional geospatial information (geology, geomorphology, and land use), topographic parameters, multispectral indices and climatic variables, added to expert opinion, remote sensing-GIS and, fieldwork facilitated the effective localization of the GDEs. The spatial scale of the parameters can be improved for future research, but the use of satellite images represented a fundamental tool to obtain most of the parameters used. In addition, the Google Earth Engine technology platform facilitated the rapid analysis of satellite information and it can be applied in geospatial investigations at world level. In this study the lack of adequate spatial distribution of observation wells limited our ability to obtain a GW map, and the absence of soil type information was another limitation. These variables were considered in the initial stage of the study but could not be used. Our method used data from 2002-2003 and 2016-2017 due to information availability, but greater temporal scale and use of images with a greater spatial resolution to analyze GDE dynamics in detail are recommended.

4. Conclusions

This study proposes a new geospatial method with an integrated, temporal approach that allows potential groundwater-dependent ecosystem zones to be mapped and their spatio-temporal changes to be analyzed. The parameters considered predictors of GDE presence were assigned weights through surveys of experts; the most important were geology, rainfall, LULC, geomorphology, and the NDVI. Of the 18 layers initially identified, only 14 were used in the multicritera analysis. The PGDEZ maps obtained for 2002 and 2017 showed zones of very high, high, medium, low and very low probability of presence of these ecosystems. The field validation confirmed the presence of GDEs at all the visited sites (100%). It was shown that the GDEs ("very high" and "high" classes) decreased in area, with those in the "high" class undergoing the greatest reduction (7.4%), while those in the "very high" class decreased by only 0.7%. The geospatial parameters of a temporal nature most sensitive to PGDEZ changes between 2002 and 2017 were rainfall and LULC, the former of which had a slightly greater influence than human activities. In addition, it was demonstrated that the NDVI of the GDEs decreased significantly, particularly from 2010 on, and that this decrease was more influenced by GW than by rainfall, showing the close relationship between the GDEs and groundwater and the effectiveness of the proposed method.

This study highlights the efficiency of Remote sensing and GIS, complemented by expert opinion and field validation, at identifying potential GDE zones, as well as the importance of this new method for annual-scale analysis of the spatio-temporal changes in these ecosystems. The method can be used in other arid and semi-arid environments and contributes to the sustainable management of GDEs amid current climate and anthropogenic changes.

Author contributions: Conceptualization: I.D-Ll, O.R, J.L.A; Data curation: I.D-Ll, R.M; Formal analysis: I.D-Ll; Funding acquisition: I.D-Ll, J.L.A; Investigation: I.D-Ll; Methodology: I.D-Ll, L.A; Project administration: I.D-Ll; Resources: I.D-Ll, J.L.A; Software: I.D-Ll, L.G-R; Supervision: J.L.A, M.A, O.R; Validation: I.D-Ll, J.L.A, R.M; Visualization: I.D-Ll, R.O, S.K, L.R-L; Roles/Writing - original draft: I.D-Ll; Writing - review & editing: I.D-Ll, J.L.A, R.O, M.A, O.R, S.K, L.R-L, L.G-R; L.A.

Declaration of Competing Interest: The authors declare that they have no conflicts of interest.

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Appendix A

Table 4.A.1. Review of literature between 2003 and 2020.

Years	Sources reviewed	Papers and books	Scientific Reports	GDE	Mapping and Changes in GDE	General conceptualization	GWPZ
2003	1	1	0	1	0	1	0
2004	0	0	0	0	0	0	0
2005	2	2	0	1	0	1	1
2006	8	5	3	8	1	7	0
2007	3	3	0	2	2	0	1
2008	0	0	0	0	0	0	0
2009	4	2	2	3	1	2	1
2010	8	5	3	7	6	1	1
2011	8	8	2	8	4	4	0
2012	7	5	2	7	5	2	0
2013	5	4	1	3	2	1	2
2014	10	10	0	9	4	5	1
2015	17	15	2	15	10	5	2
2016	19	17	2	17	11	6	2
2017	11	10	1	11	6	5	0
2018	9	8	1	6	4	2	3
2019	25	22	2	16	11	5	9
2020	21	20	1	11	7	4	10
Total	**158**	**137**	**22**	**125**	**74**	**51**	**33**

Table 4.A.2. Geospatial parameters not used in the final model.

Parameters	Weight (%)	Scale or Potential	Class	Rank	Reference
EVI	7.6	Very low Low Medium High Very High	< 0 0-0.1 0.1-0.2 0.2-0.4 0.4-1	1 2 3 4 5	(Dresel et al., 2010; Kuginis et al., 2016)
Dd	6.4	Very low Low Medium High Very High	0.3-1.1 1.1-1.6 1.6-2.1 2.1-2.8 2.8-3.5	1 2 3 4 5	Local expert opinion (Mallick et al., 2019; Nhu et al., 2020)
Sp	1.7	Very High High Medium Low Very low	0-5 5-10 10-16 16-26 >26	5 4 3 2 1	(Andualem and Demeke, 2019; Marques et al., 2019; Münch and Conrad, 2007)

Parameters	Weight (%)	Scale or Potential	Class	Rank	Reference
TRI	0.5	Very High Hight Medium Low Very low	0-0.25 0.25-0.45 0.45-0.55 0.55-0.65 0.65-0.92	5 4 3 2 1	Local expert opinion (Arulbalaji et al., 2019)

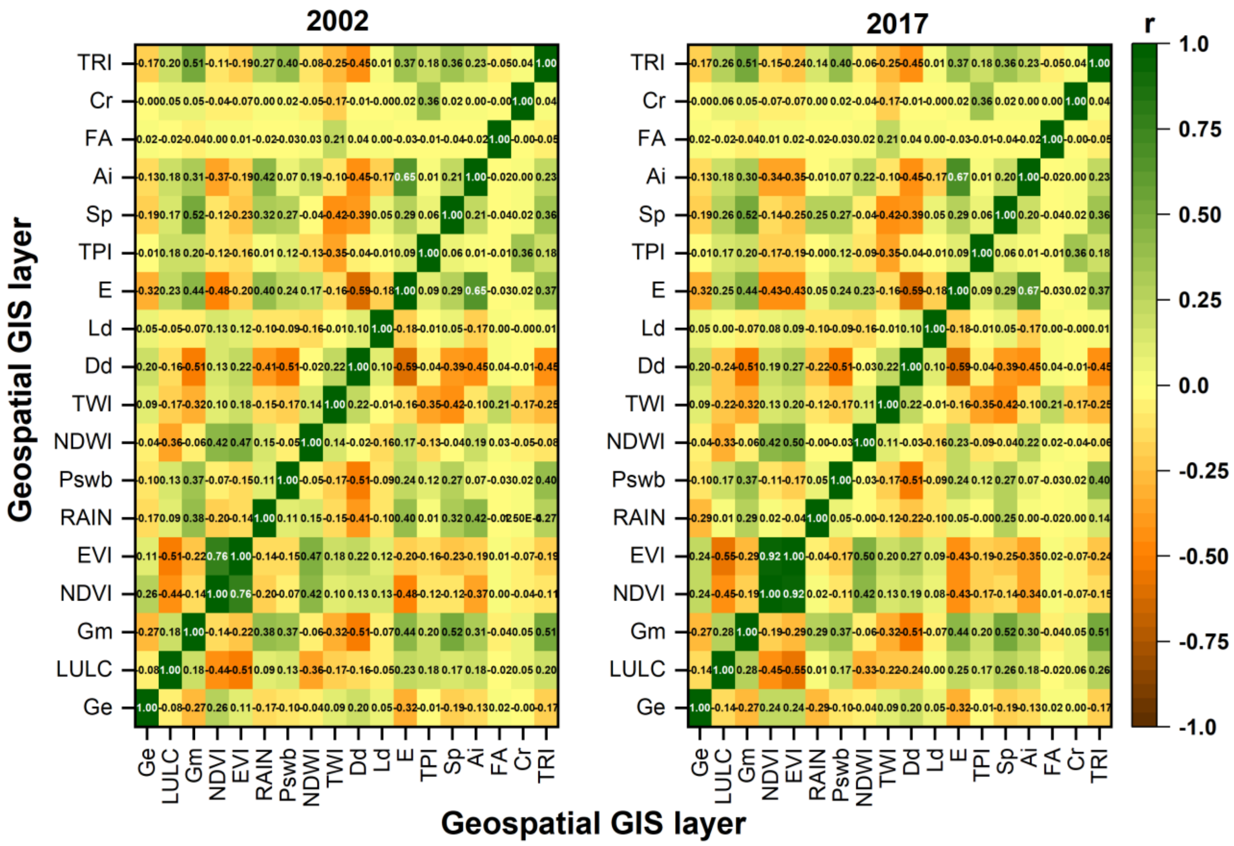

Figure 4.A.1. Correlation plot of all geospatial parameters.

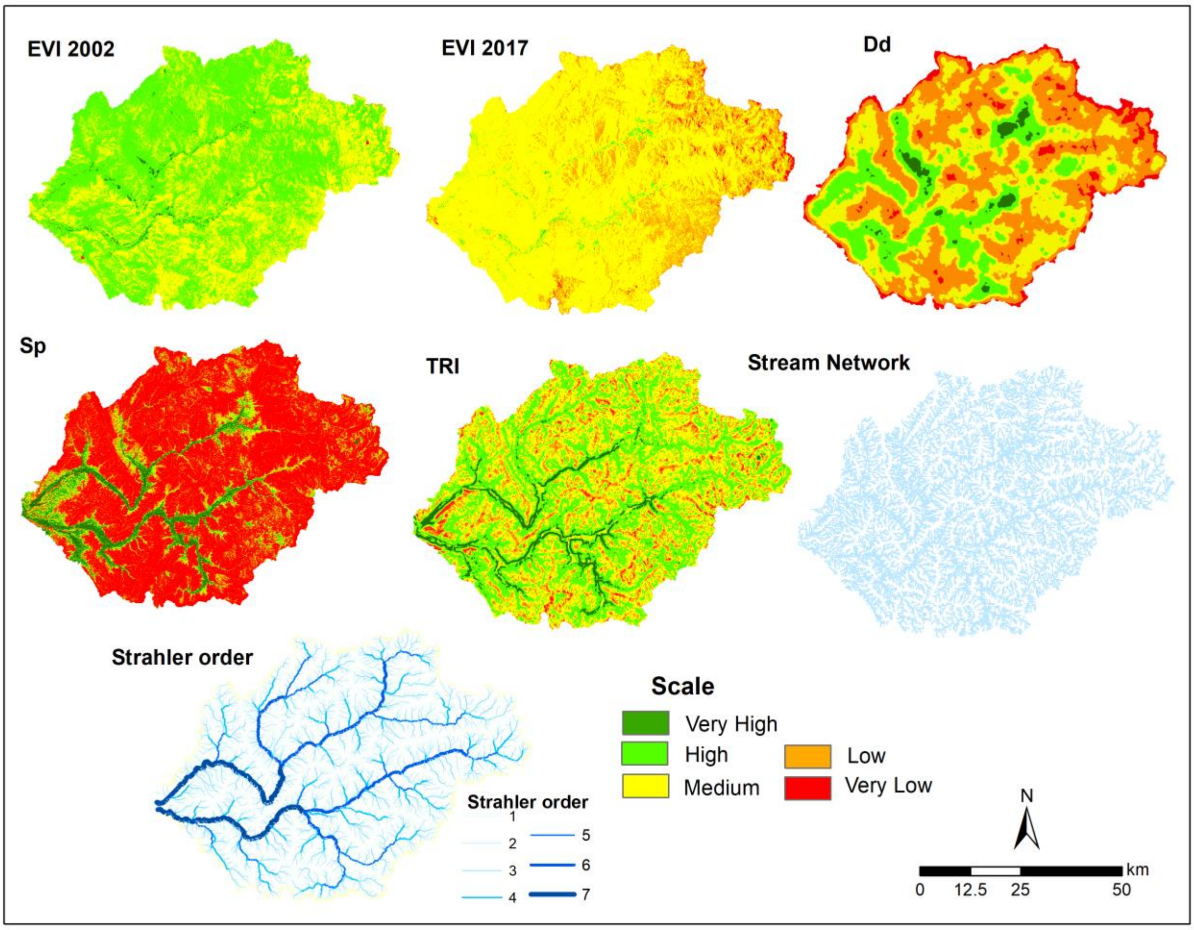

Figure 4.A.2. Geospatial parameters not used in the final model and the water network and Strahler order maps.

Table 4.A.3. Sensitivity analysis results.

Surface	GDEPZ	All Parameters	LULC	NDVI	NDWI	Rain	Ai
2002 (%)	Very High	1.36	-0.17	-0.62	+0.57	**+2.16**	-0.19
	High	20.04	-1.89	-4.20	+1.00	**+5.50**	-0.78
	Medium	62.58	**-8.40**	-7.51	-2.34	-5.42	-0.11
	Low	10.00	**+16.42**	+11.80	+0.70	-2.22	+0.94
	Very low	6.01	**-5.96**	+0.52	+0.07	-0.02	+0.13
2017 (%)	Very High	0.64	+0.03	**+0.91**	+0.52	-0.13	+0.13
	High	12.61	**+4.65**	+4.54	+4.63	-3.34	-0.09
	Medium	58.08	**-8.44**	+1.67	+2.06	-7.23	-1.38
	Low	20.59	**+11.56**	-6.08	-7.22	+10.26	+1.46
	Very low	8.08	**-7.80**	-1.04	+0.01	+0.43	-0.12
Change (%)	Very High	-0.72	+0.20	+1.53	-0.05	**-2.17**	+0.06
	High	-7.43	+6.54	+8.74	+3.63	**-8.84**	+0.69
	Medium	-4.50	-0.04	**+9.17**	+4.39	-1.94	-1.27
	Low	10.58	-4.86	**-17.88**	-7.92	+12.48	+0.52
	Very low	2.08	**-1.84**	-1.57	-0.06	+0.46	+0.01

* Bold values represent the parameter with the greatest influence in %.

Table 4.A.4. Statistical indicators for analysis between NDVI-R and NDVI-GW.

GDE Polygons	NDVI-R		NDVI-GW	
	r Pearson	R^2	r Pearson	R^2
1	0.51	0.26	0.88	0.78
2	0.51	0.26	0.81	0.67
3	0.46	0.21	0.92	0.85
4	0.33	0.11	0.43	0.19
5	0.27	0.07	0.74	0.54
6	0.27	0.07	0.79	0.63
7	0.58	0.33	0.88	0.78
8	0.74	0.54	0.69	0.47
9	0.56	0.31	0.77	0.59
10	0.54	0.3	0.94	0.88
11	0.45	0.21	0.88	0.78
12	0.67	0.41	0.81	0.65
13	0.34	0.11	0.61	0.36
14	0.56	0.31	0.3	0.09
15	0.48	0.23	0.74	0.55
16	0.46	0.21	0.8	0.64
17	0.52	0.22	0.8	0.64

* The results present a significance of p-value > 0.001

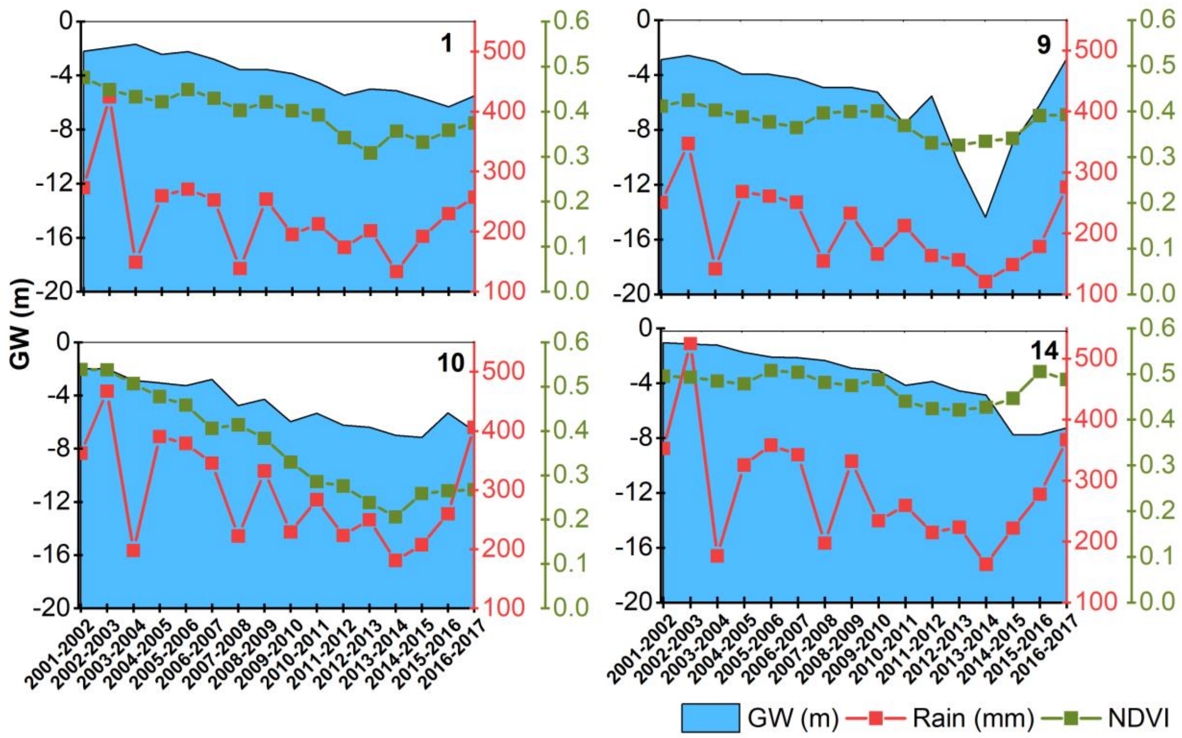

Figure 4.A.3. Time series of average summer NDVI, average annual GW, and annual rainfall by PGDEZ polygon. 1) and 9) in Petorca watershed, and 10) and 14) in Ligua watershed.

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CAPÍTULO V. DISCUSIÓN GENERAL

IV.1 Evaluación de los cambios en la agricultura con el agotamiento de las aguas subterráneas en las cuencas La Ligua y Petorca (H1).

El GW es el principal recurso de agua líquida y dulce del planeta (Liu et al., 2021). En muchas zonas semiáridas, específicamente en las cuencas hidrográficas La Ligua y Petorca de la región de Valparaíso, es la única fuente de agua disponible durante los períodos secos. En estas cuencas se han generado grandes conflictos sociales por el derecho humano al agua, que son atribuidos por algunas fuentes a la sequía, pero otros apuntan a las prácticas del agronegocio en un modelo de gestión hídrica. Por tanto, en esta investigación se profundizó en los posibles factores desencadenantes de este agotamiento.

En el período 2002-2017 fue evidente una disminución de las GW al analizar el comportamiento por pozo de observación en ambas cuencas. El mayor descenso ocurrió en algunos pozos del valle central de La Ligua, lo que indica la influencia de factores locales de carácter antrópico, mientras que las precipitaciones se comportaron de manera homogénea en las cuencas, es decir, sin diferencias espaciales y temporales. Además, los valores de GW estandarizados mostraron diferencias espaciales entre las dos cuencas hidrográficas, mientras que el SPI fue espacialmente homogéneo. El período 2009-2015 fue el más crítico y se encontró una relación entre las GW y el SPI, principalmente en las escalas temporales de 9 a 24 meses, lo que indicó el vínculo de las GW con un período de sequía. Esta sequía manifestada con anomalías de precipitaciones en escalas temporales largas (9, 12 y 24 meses), refleja los efectos sobre las aguas superficiales y subterráneas, por ende, se puede asociar a una sequía hidrológica, tal como lo expresa la Organización Meteorológica Mundial (OMM, 2016; Svoboda et al., 2012; Zou et al., 2018). Al mismo tiempo, este índice mostró valores alrededor de los 1.5 en los meses más críticos, por lo tanto, esta sequía se clasifica como *moderada* según la clasificación de McKee et al.(1993) y luego modificada por Yao et al.(2018). No obstante, aunque no se considera tan intensa (según la clasificación del SPI), fue la más prolongada de los últimos 36 años (1981-2016). Esta sequía es abordada también por Garreaud et al. (2017) en un estudio realizado a todo el Centro-Sur de Chile. Este investigador denominó a este fenómeno natural como *megasequía* y con una duración del 2010 hasta el 2015. En publicaciones posteriores de este investigador se ha confirmado que este fenómeno continua manifestándose (Garreaud et al., 2019). Otras investigaciones han profundizado en la dinámica climática de esta sequía y en los impactos negativos sobre el régimen hidrológico (Aldunce et al., 2017; Bozkurt et al., 2017; Muñoz et al., 2020). Los resultados demuestran una relación entre las GW y la sequía, pero no se puede afirmar que exista una tendencia en el comportamiento de las precipitaciones y que esté relacionada directamente con la disminución significativa del GW. Esta afirmación es ratificada con los valores bajos en el análisis de correlación entre estas variables (Duran-Llacer et al., 2020).

Para el período analizado en esta Tesis, los años más críticos fueron del 2012 al 2014 en tanto términos de GW y precipitaciones, como en el comportamiento del NDVI. A través de una revisión del registro de frutas de la Oficina de Estudios y Políticas Agrícolas (ODEPA) entre 2008 y 2014, se pudo confirmar que, en el 2014, el área plantada de paltos en las cuencas había disminuido, lo que puede ser consecuente con la disminución del NDVI en estos años. A pesar de esta problemática se siguió extrayendo GW para riego, que según estos resultados indican que la mayor extracción de GW era destinada al riego del palto. En Ayala et al. (2014), también se discutió la disminución en los niveles de los pozos y la dificultad de cuantificar la cantidad real de variación del nivel del agua utilizando datos históricos de bombeo en el área, ya que estaba experimentando una extracción irregular de recursos hídricos. Celedón, (2019) afirmó que 2010 fue el año con mayor uso de GW para riego, ya que fue el año con mayor cantidad de tierra cultivada y menor disponibilidad de agua superficial. Estas ideas muestran que se estaba extrayendo una gran cantidad de agua en los valles estudiados, tal como se demostró en esta investigación.

A través de esta investigación se pudo confirmar que el factor agrícola jugó el papel más importante en el agotamiento de los acuíferos. La sequía afectó ambos valles con la misma intensidad, pero los cultivos de La Ligua se mantuvieron en su mayor extensión y se continuó expandiendo el palto hacia los cerros. Aunque disminuyó la recarga local de las GW por medio de la lluvia, se continuó con el riego agrícola y por ende, con la extracción de GW sin tener en cuenta la sostenibilidad de los acuíferos. En Petorca, el efecto generado por la agricultura sobre el nivel de las GW fue menor respecto a La Ligua, ya que el aumento de la superficie agrícola fue menor, así como el descenso de las GW. No obstante, aunque algunas áreas dedicadas al palto fueron abandonadas, otras se mantuvieron o aumentaron principalmente hacia algunos cerros o zonas altas de la cuenca. Además, se continuaron otorgando derechos de GW y se incrementaron los embalses. Estos reservorios artificiales fueron construidos por el gobierno chileno para “mitigar” los efectos de la sequía, según Bolados et al. (2017) y Panez-Pinto et al. (2017), pero con base a los resultados de esta investigación, esta medida tomada pudo haber tenido el efecto contrario. Un resultado importante fue que los pozos con mayores descensos estaban ubicados en zonas donde aumentaron o se mantuvieron las áreas dedicadas al palto. Este frutal de origen tropical requiere un gran suministro de agua durante todo el año para un adecuado crecimiento vegetativo y productivo (Carr, 2013; Holzapfel et al., 2017; INIA , 2017). En efecto, las necesidades de agua para lograr los mayores rendimientos en una región mediterránea son de más de 7 500 m^3/a (Moreno-Ortega et al., 2019), por tanto, el aumento o mantenimiento de este cultivo repercutió en el uso y extracción de GW.

En otras investigaciones se ha estudiado desde el punto de vista socio-ecológico, el tema de los derechos de las aguas en la provincia de Petorca en relación con el palto (Bolados et al., 2017; Panez-Pinto et al., 2018; Roose and Panez, 2020). Varios han sido los conflictos sociales acontecidos en Petorca por el derecho humano al agua, la agroindustria y la usurpación de GW. La superficie ocupada por plantaciones de palto fue aumentando desde la década de los años 90 hasta convertirse en zona exportadora de esta fruta hacia grandes mercados internacionales de China y Europa. Las desigualdades en materia de derechos de agua fueron creciendo debido a este aumento desmedido de la mono exportación y a la legislación impuesta durante la dictadura militar (Código de Aguas). Los resultados mostrados en esta Tesis confirman estos antecedentes. La superficie del palto es superior respecto a otros cultivos y su expansión se ha realizado principalmente hacia valles y cerros. Se continuó otorgando derechos de aguas a perpetuidad y sin costo, y concentrados en los principales empresarios dedicados al cultivo del palto. Es importante resaltar que los derechos de las GW presentaron una alta correlación estadística con el descenso de las GW y que si bien, el número de derechos otorgados disminuyó en los últimos años, probablemente debido a las medidas tomadas por el gobierno y la DGA, el efecto aún es notorio y acumulativo, con repercusiones en el agotamiento de los acuíferos.

Los resultados mostraron una sobreexplotación de las GW ya que existe un desequilibrio entre la disponibilidad y la demanda. Esto demuestra que la gestión de las GW en las cuencas no es sostenible. Desde el inicio de la agroindustria y la privatización del agua en la zona, la gestión hídrica ha estado ausente a pesar de los grandes esfuerzos realizados por los habitantes, la DGA y diferentes organizaciones sociales vinculadas el derecho humano al agua, como es el caso del Movimiento de Defensa del Agua, la Tierra y el Medioambiente (MODATIMA). Todo esto indica la necesidad de una gestión sostenible de las GW. Todas las evidencias anteriores permiten aceptar la hipótesis planteada (H1).

IV.2 La influencia del cambio de almacenamiento de los acuíferos en los Ecosistemas Dependientes de las Aguas Subterráneas (H2).

El uso de las GW se ha intensificado en las últimas décadas debido a la creciente demanda del riego agrícola y al cambio climático, por lo que los GDE pueden verse amenazados (Rohde et al., 2019). En este estudio se utilizó un método geoespacial novedoso para el mapeo de Zonas Potenciales de GDE. El mismo permite el análisis anual de los cambios espacio-temporales de estos ecosistemas. Pocos estudios han utilizado enfoques similares en cuanto al empleo del criterio de experto y técnicas de sensoramiento remoto unido a los SIG para el mapeo de los GDE (Doody et al., 2017; Glanville et al., 2016b). Varias investigaciones han empleado estos métodos para el mapeo de zonas de recargas de GW (Andualem and Demeke, 2019; Mallick et al., 2015; Mokadem et al., 2018; Nhu et al., 2020). No obstante, estas investigaciones no han tenido el carácter integral en relación con los datos cartográficos empleados, ni el carácter temporal en el sentido de obtener mapas con dinámicas temporales. Además, los mayores esfuerzos destinados al estudio de los GDE se han concentrado en los ecosistemas de vegetación dependientes de las GW, no siendo considerados todos los ecosistemas terrestres y acuáticos que son clasificados como GDE. Estas características le confieren a este método una novedad de gran importancia.

Los parámetros a los que se le otorgó mayor peso fueron la geología, la lluvia, el LULC, la geomorfología y el NDVI, según los criterios obtenidos de la encuesta. Luego cada parámetro fue reclasificado en 5 rangos y normalizados desde 1 a 5 (Münch and Conrad, 2007) acorde al criterio local de experto y a las fuentes bibliográficas. La geología se reclasificó en 5 clases según el tipo de sustrato y la capacidad de favorecer la interacción GW-aguas superficiales-vegetación terrestre. El mapa geomorfológico se obtuvo después de emplear la técnica de fotointerpretación y digitalización de las unidades geomorfológicas presentes a través de imágenes Landsat, y el mayor potencial (clase “muy alta”) se le otorgó a la zona de valles con depósitos fluvio-aluviales. Los principales criterios para esta clasificación fueron las características del sustrato, la capacidad de interacción entre GW y aguas superficiales, y condiciones de menor ondulación del relieve. El LULC se reagrupó en 9 categorías según los intereses del estudio. A las rocas se le asignó la clase Baja y los otros usos se otorgaron clases según las características y cercanías a los valles de la vegetación. Por su parte a las zonas agrícolas, reservorios y áreas urbanas se consideraron como una clase excluyente, ya que a la mayoría de las tierras agrícolas y paisajes dominados por la acción antrópica no se consideran como GDE (Klausmeyer et al., 2018). La elevación óptima para localizar un GDE fue hasta los 800 m, de 800 m a 1600 m fue catalogada como “alta” y a medida que aumentó la altura el potencial otorgado fue menor. La proximidad a cuerpos de agua, índice de humedad topográfica, densidad de lineamientos e índice de posición topográfica, se le asignaron las clases según los valores de cada parámetro, es decir, a los rangos cercanos a cero se le asignaron los pesos más altos, y viceversa para los demás rangos. En el caso de la acumulación de flujo, que es una técnica que permite extraer celdas con alta acumulación de flujo (canales de arroyos), también fue considerado las celdas que comprendían toda la superficie de acumulación, ya que podrían interpretarse como áreas de humedad, y por tanto, áreas potenciales para encontrar un GDE (Münch and Conrad, 2007). Por su parte, a los valores negativos de la curvatura, se le asignaron las escalas “muy alta” y “alta”, ya que representan zonas cóncavas (áreas bajas o depresiones), mientras a los valores positivos (superficie convexa) se le otorgaron las escalas más bajas (Dar et al., 2010). También a los rangos de los mayores valores de los índices multiespectrales se le asignaron los más altos potenciales. En el caso del NDVI se observó una disminución en el verdor de la vegetación entre el 2002 y el 2017, como posible consecuencia del agotamiento significativo de las GW o de la megasequía (Duran-Llacer et al., 2020). Las variables climáticas (lluvia e índice de aridez) también mostraron un descenso de sus valores, lo que refleja la presencia de la sequía y el aumento del grado de aridez. A los menores valores de estas variables se le asignaron las clases de potencial muy alto y alto, ya que en un clima húmedo, donde las necesidades de los ecosistemas se satisfacen mediante las precipitaciones, es de baja probabilidad que dicho ecosistema dependa del GW, por tanto, entre menor pluviosidad, mayor probabilidad de la presencia de un GDE (Hoyos et al., 2015; Marques et al., 2019).

En los mapas de PGDEZ obtenidos, la clase "muy alta" se encontró principalmente en los valles de los ríos donde existe una gran interacción entre GW y aguas superficiales, correspondiente a zonas llanas. La clase "alta" presentó una distribución similar que la anterior, pero en mayor proporción y se caracterizó por zonas llanas, mayor humedad del suelo, vegetación más densa, rocas sedimentarias y un mayor grado de aridez. Ambas clases representan la mayor probabilidad de encontrar un GDE que pueden ser tanto terrestres como acuáticos e incluir ríos, vegetación ribereña, praderas, árboles y arbustos, manantiales, humedales y ecosistemas estuarinos. La clase "media" se caracterizó por pequeños valles en zonas más elevadas, mientras la "baja", estuvo mayormente representada por los cordones transversales y las zonas más elevadas de las cuencas. La clase "muy baja" fue asociada a la presencia de tierras agrícolas que se extienden por los valles principales y alrededor de ríos y GDE, además de zonas de alta pendiente en la precordillera, los embalses y las áreas construidas.

Las clases "muy alta" y "alta" disminuyeron en superficie entre el 2002 y el 2017, lo que indica una pérdida de los GDE y de las condiciones para su desarrollo. La clase "media" también disminuyó, pero las clases "baja" y "muy baja", aumentaron, indicando la expansión de las tierras agrícolas en ese período. Al evaluar los cambios a nivel de cuenca, se pudo contactar que en Petorca ocurrió un muy ligero aumento de la clase "muy alta", mientras que, en La Ligua, ocurrieron los mayores y descensos de las restantes categorías. Esto responde al mayor aumento de las tierras agrícolas y al descenso más acentuado de las GW en La Ligua (Duran-Llacer et al., 2020).

Al visitar 100 puntos previamente seleccionados en los mapas se comprobó que en su totalidad los sitios manifestaron la presencia de GDE (clase "muy alta" y "alta"). Se encontró GDE con vegetación en buen estado vegetativo o coloración verde que indicó el aporte del GW a estos ecosistemas. Algunos tipos de arbustos y árboles de raíces profundas (freatófitas) fueron localizados a lo largo de gradientes naturales de humedad, indicando el aporte de GW a través de un manantial. En solamente 10 puntos se observó un deterioro evidente en la salud y vigor de la vegetación, lo que evidencia la respuesta ecohidrológica a los cambios hidroclimáticos y antrópicos de estos ecosistemas. Luego al excluir cada parámetro de carácter temporal (LULC, lluvia, NDVI, NDWI, índice de aridez) se comprobó que la lluvia fue el parámetro más sensible a los cambios de las clases "muy alta" y "alta", por lo que la influencia de la lluvia fue ligeramente mayor que las actividades antrópicas en los cambios espacio-temporales de los GDE. El NDVI de los polígonos identificados como GDE disminuyó significativamente en el período estudiado (82.3 %), con un descenso más pronunciado hacia el 2010, al igual que las GW y la lluvia. Esto evidencia la relación que existe entre el vigor de la vegetación de los GDE con el GW y la lluvia, tal como lo expresó Huntington et al.(2016). Se encontraron además, puntos de cambio significativos en la serie de tiempo NDVI, en un 94 % (16 GDE), entre 2009 y 2011, pero el 2010 representó el año más frecuente en los cambios de la serie de tiempo. Los resultados de la correlación y la regresión lineal corroboraron la relación entre estas variables, pero también demostraron que las GW y los GDE estaban más relacionados respecto a la lluvia, ya que en 15 polígonos GDE (88 %) se presentó una mayor correlación lineal entre GW y NDVI. Esto demuestra que los GDE se vieron afectados mayormente por la disminución del GW que por la disminución de la lluvia y que el método propuesto efectivamente constituye una herramienta para el mapeo de estos ecosistemas. En solo 3 polígonos los indicadores estadísticos fueron bajos, pudiendo ser consecuencia de la influencia de las zonas agrícolas y la lluvia. Es importante resaltar que la profundidad del nivel del agua antes del 2010 no superó los 10 m, lo que cumple con el umbral necesario para que la vegetación dependiente pueda acceder al GW según Eamus et al. (2015) y Rohde et al. (2019). Esto representa otra forma de validación del método. Después del 2010 el nivel freático disminuyó, lo que incidió en la disminución y degradación de los GDE. Esta respuesta ecohidrológica a la disminución acuífera, representa cambios en la productividad, biodiversidad y provisión de servicios ecosistémicos, tal como se expresa en (OGIA, 2019).

Este método destaca la eficiencia de la teledetección y los SIG complementados con el criterio de experto y la validación en terreno para identificar zonas potenciales de GDE. La metodología propuesta es aplicable a otras regiones áridas y semiáridas, pero se debe tener en cuenta la calidad y cantidad de información. Obtener un nuevo método de análisis a escala anual de los cambios espacio-temporales de los GDE fue un gran logro de esta investigación. El abordaje integral logrado mediante el uso de diferentes parámetros geoespaciales como la información geoespacial convencional (geología, geomorfología y uso del suelo), parámetros topográficos, índices multiespectrales y variables climáticas, sumados a la opinión de expertos, teledetección-GIS y, el trabajo de campo facilitó la efectiva localización de estos ecosistemas tan poco estudiados. Gracias al método propuesto se pudo analizar los cambios espacio-temporales de los GDE desde el 2002 hasta el 2017. En efecto, quedó demostrado que estos ecosistemas se vieron afectados por el cambio de almacenamiento de los acuíferos en los últimos años, por lo que se acepta la hipótesis H2.

IV.3 Medidas propuestas para la Gestión de las Aguas Subterráneas y los Ecosistemas Dependientes.

Ante la problemática del agotamiento de las GW, su relación directa con la agricultura y la disminución de los GDE en las cuencas La Ligua y Petorca, se hace imprescindible la toma de acciones para la gestión de los recursos hídricos subterráneos. La DGA ha instaurado varios instrumentos de gestión como la creación de las Comunidades de Usuarios de Aguas Subterráneas, declaraciones de escases hídrica y declaraciones de zonas de restricción de GW, pero la realidad es que no han sido efectivos. Por tanto, se proponen las siguientes medidas:

- Fortalecer la inversión y la colaboración de los usuarios locales del agua, las partes interesadas y los tomadores de decisiones a través de acciones que favorezcan los intercambios y las discusiones.

- Establecer acuerdos científicos y políticos entre agencias académicas y gubernamentales, tanto en las cuencas como en territorios cercanos, con el objetivo de implementar un sistema de gestión y mejoras en las prácticas agrícolas ante escenarios de sequías.

- Crear una nueva reforma del Código de Aguas, que incluya una mayor regularización y fiscalización de los derechos otorgados de las GW, el caudal ecológico y controle las extracciones legales e ilegales de los acuíferos.

- Establecer nuevas normativas que garanticen que la capacidad de abastecimiento de los acuíferos no supere su volumen sostenible, por ejemplo, establecer límites en las tasas de bombeo (Donoso et al., 2020).

- Implementar la participación ciudadana como un mecanismo de gestión activo en la toma de decisiones y reorientación de políticas públicas a favor de las comunidades.

- Incluir en el marco legal mecanismos que garanticen equitativamente el derecho humano al agua.

- Mayor apoyo a las Comunidades de Aguas Subterráneas para garantizar un mayor interés de los usuarios y un mayor funcionamiento de estas organizaciones ya establecidas, ya que fueron creadas para lograr la gestión de las GW (Red Agrícola, 2019).

- Construcción de plantas desalinizadoras que suplan las necesidades del riego agrícola. La tecnología de la osmosis reversa empleada en estas plantas permite eliminar la salinidad del agua del mar, lo que puede contribuir a reducir la extracción de GW para riego y ser una solución emergente ante la escasez hídrica de la región.

- Implementar Planes de Desarrollo Regional y un marco institucional para la Gestión Integrada de Cuencas Hidrográficas.

- Implementar una legislación para la protección de los GDE y definir una escala de gestión (Erostate et al., 2020).

- Priorizar aquellos GDE de mayor valor ecológico y establecer un marco regulatorio que evite extracciones cercanas de GW (Dabovic et al., 2019).

- Restaurar el sistema de GW para que estos ecosistemas se sostengan con un agua de buena calidad, así como mejoras en las prácticas del uso agrícola (Kløve et al., 2014b).

- Dictar medidas para la restauración ecológica de los GDE.

- Realizar investigaciones interdisciplinarias que determinen la vulnerabilidad de los GDE ante los cambios climáticos y antrópicos.

- Incluir a los GDE dentro del Comité Nacional de Áreas Protegidas (CNAP) del Ministerios del Medio Ambiente (MMA) y las diferentes estrategias de conservación que ya están establecidas o en alguna legislación de protección de la biodiversidad.

- Desarrollar talleres de educación ambiental con el tema de los GDE y los servicios ecosistémicos asociados, para garantizar una conciencia ciudadana en relación con la protección de estos ecosistemas.

- Diseñar plataformas interactivas para el monitoreo espacial y temporal de los GDE en las cuencas y a nivel nacional.

CONCLUSIONES GENERALES

El desarrollo de esta investigación generó información importante sobre el agotamiento de las GW en las cuencas hidrográficas La Ligua y Petorca. Se estudió el vínculo entre esta problemática ambiental con la agricultura y los ecosistemas que se sustentan de las GW. A continuación, se describen las principales conclusiones.

1. El nivel de las GW presentó una tendencia decreciente estadísticamente significativa (75 % de los pozos) en las cuencas La Ligua y Petorca, siendo más acentuada en la cuenca La Ligua a pesar de una disminución de la lluvia estadísticamente no significativa, y manifestarse de forma homogénea en todo el territorio una sequía hidrológica moderada. Esta sequía no ha sido tan intensa, pero si muy prolongada.

2. El análisis estadístico ofreció una visión precisa de la relación entre las variables estudiadas. Las correlaciones entre las GW y el índice de sequía a escalas temporales largas (SPI; 12 y 24) fueron altas, lo que mostró la relación entre el agotamiento de las GW y la sequía. Las correlaciones y correlaciones cruzadas entre GW y NDVI fueron superiores a las encontradas entre GW y lluvia, reflejando la influencia del riego. Además, la correlación entre GW y los derechos de GW resultó alta. Todos estos resultados reflejan la influencia del riego y aclaran que el agotamiento de los acuíferos estuvo influenciado mayormente por factores antrópicos.

3. A pesar de la sequía y el otorgamiento continuo de los derechos de las GW, las áreas agrícolas dedicadas a la fruticultura, principalmente el cultivo del palto, aumentaron. El mayor aumento de paltos ocurrió en la cuenca La Ligua, coincidiendo con las zonas de mayor disminución de las GW. No obstante, en Petorca, también se presentaron áreas donde aumentó o se mantuvo este cultivo, junto a un aumento de los embalses.

4. El aumento en la alta demanda de agua o la concesión excesiva de derechos GW, asociados con la sobreexplotación por parte de la agricultura debido al aumento de la superficie del palto, el riego y los embalses, junto con la falta de una gestión sostenible de los recursos hídricos, confirmó que el agotamiento de las GW fue mayoritariamente influenciado por factores humanos y no por factores climáticos. Por lo que los cambios relacionados con la actividad agrícola (uso del suelo y derechos de las GW) contribuyeron significativamente al agotamiento de los acuíferos.

5. A través de un análisis multicriterio, este estudio propuso un nuevo método con un enfoque integrado y temporal, que permitió mapear Zonas Potenciales de Ecosistemas Dependientes de las GW y analizar sus cambios espacio-

temporales ante el nivel cambiante de las GW entre el 2002 y el 2017.

6. Se obtuvieron 26 encuestas completas de expertos nacionales e internacionales en GDE y Tecnologías de la Información Geográfica. Las respuestas presentaron un buen consenso entre ellas, lo que permitió asignar pesos a 18 parámetros geoespaciales que eran considerados predictores para mapear estos ecosistemas. Los parámetros más importantes fueron la geología, la lluvia, el LULC, la geomorfología y el NDVI. Luego de un análisis estadístico se consideraron solo 14 parámetros a emplear en el modelo multicriterio.

7. Los mapas PGDEZ obtenidos mostraron zonas de muy alta, alta, media, baja y muy baja probabilidad de encontrar GDE. Las clases consideradas como GDE (muy alta y alta), disminuyeron en superficie, siendo la clase “alta” la de mayor descenso (0.7 % y 7.4 %, respectivamente). Este comportamiento resultó diferente entre cuencas, ya que en Petorca la disminución de la zona “muy alta” fue muy ligeramente superior que, en La Ligua, además de que los mayores aumentos y descensos de las restantes categorías ocurrieron en La Ligua. Lo que responde al mayor aumento de superficie frutícola y al descenso más acentuado de las GW en esta cuenca.

8. Los parámetros geoespaciales de carácter temporal que más influyeron en los cambios espacio-temporales de los GDE fueron la lluvia y el uso del suelo, siendo la lluvia el de ligeramente mayor influencia respecto a las actividades antrópicas. No obstante, se demostró a través del NDVI de verano, que la disminución de los GDE, más acentuada a partir del 2010, estaba mayormente influenciada por el agotamiento de las GW respecto a la lluvia (r Pearson $\geq$ 0.74). En base a lo anterior, se comprobó la estrecha relación entre estos ecosistemas con las GW, la efectividad del método propuesto y que los GDE se vieron afectados ante el agotamiento de los acuíferos.

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Anexos

Anexo 1. Portada de Artículos publicados

water

MDPI

Article

Lessons to Be Learned: Groundwater Depletion in Chile's Ligua and Petorca Watersheds through an Interdisciplinary Approach

Iongel Duran-Llacer [1,*], Juan Munizaga [1], José Luis Arumí [2], Christopher Ruybal [3], Mauricio Aguayo [1], Katia Sáez-Carrillo [4], Loretto Arriagada [1] and Octavio Rojas [1]

1 Faculty of Environmental Sciences and EULA-Chile Center, Department of Territorial Planning, University of Concepcion, Víctor Lamas 1290, Concepción 4070386, Chile; juanmunizaga@udec.cl (J.M.); maaguayo@udec.cl (M.A.); nancyarriagada@udec.cl (L.A.); ocrojas@udec.cl (O.R.)
2 Department of Water Resources, CHRIAM Water Center, University of Concepcion, Vicente Mendez 595, Chillán 3812120, Chile; jarumi@udec.cl
3 U.S. Fulbright Program-Chile, Department of Water Resources, University of Concepcion, Chillán 3812120, Chile; cruybal@mymail.mines.edu
4 Department of Statistics, Faculty of Physical and Mathematical Sciences, University of Concepcion, Víctor Lamas 1290, Concepción 4070386, Chile; ksaez@udec.cl
* Correspondence: ioduran@udec.cl or iongel.duran@gmail.com

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Abstract: Groundwater (GW) is the primary source of unfrozen freshwater on the planet and in many semi-arid areas, it is the only source of water available during low-water periods. In north-central Chile, there has been GW depletion as a result of semi-arid conditions and high water demand, which has unleashed major social conflicts, some due to drought and others due to agribusiness practices against the backdrop of a private water management model. The Ligua and Petorca watersheds in the Valparaíso Region were studied in order to analyze the influence of climatic and anthropogenic factors on aquifer depletion using an interdisciplinary approach that integrates hydroclimatic variables, remote sensing data techniques, and GW rights data to promote sustainable GW management. The Standardized Precipitation Index (SPI) and Normalized Difference Vegetation Index (NDVI) were calculated and the 2002–2017 land-use change was analyzed. It was shown that GW decreased significantly (in 75% of the wells) and that the hydrological drought was moderate and prolonged (longest drought in the last 36 years). The avocado-growing area in Ligua increased significantly—by 2623 ha—with respect to other agricultural areas (higher GW decrease), while in Petorca, it decreased by 128 ha. In addition, GW-rainfall correlations were low and GW rights were granted continuously despite the drought. The results confirmed that aquifer depletion was mostly influenced by human factors due to overexploitation by agriculture and a lack of water management.

Keywords: groundwater depletion; drought; NDVI time series; land-use change; agriculture; groundwater rights; groundwater resources management

1. Introduction

Groundwater (GW) is a very valuable resource as it accounts for 96% of the planet's unfrozen freshwater [1]. As a part of the hydrological cycle, GW is an essential source of water for human use and agricultural and industrial activities [2], as well as the main source of water in arid and semi-arid regions [3,4]. It is estimated to supply 36% of drinking water, 42% of irrigation water, and 24% of industrial water worldwide [1].

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Anexo 2. Listado de investigadores encuestados como parte de la publicación 2.

No.	Investigador	Institución	País	Email
1	José Luis Arumí	Departamento de Recursos Hídricos, Universidad de Concepción	Chile	arumi.joseluis@gmail.com
2	Ricardo Oyarzún	Departamento Ingeniería de Minas, Universidad de la Serena	Chile	royarzun@userena.cl
3	Chrystopher Ruyball	Colorado School of Mines	USA	cruybal@mymail.mines.edu
4	Mauricio Aguayo Arias	Facultad de Ciencias Ambientales y Centro EULA	Chile	maaguayo@udec.cl
5	Félix Pérez	Hídrica Consultores	Chile	fperez@hidricaconsultores.cl
6	Lawtence Stevens	Museum of Northern Arizona	USA	farvana@aol.com
7	Saravanan Subbarayan	National Institute of Technology Tiruchirappalli	India	ssaravanan@nitt.edu
8	Eric Sandoval	Universidad de la Serena	Chile	eric.sandoval.a@gmail.com
9	Todd Caldwell	USGS	USA	tcaldwell@usgs.gov
10	Moya Tomlinson	Ecosystem Management, University of New England	Australia	moyatomlins@gmail.com
11	Katharine Glanville	Queensland Herbarium	Australia	katharine.glanville@des.qld.gov.au
12	Mélanie Erostate	Université de Corse	Francia	melanie.erostate@gmail.com
13	Pekka Rossi	University of Oulu	Finlandia	pekka.rossi@oulu.fi
14	Laurel Saito	The Nature Conservancy-Nevada	USA	laurel.saito@tnc.org
15	Kirk Klausmeyer	The Nature Conservancy	USA	kklausmeyer@tnc.org
16	Sangam Shrestha	AIT	Thailand	sangam@ait.ac.th
17	África de la Hera	Geological and Mining Institute of Spain	España	a.delahera@igme.es
18	Joe Gurrieri	US Forest Service	USA	joe.gurrieri3@gmail.com
19	Carlos Miraldo Ordens	University of Queensland	Australia	c.ordens@uq.edu.au
20	Tanveer Dar	Indian Institute of Technology Roorkee	India	tdar@es.iitr.ac.in
21	Amit Bera	Indian Institute of Engineering Science and Technology, Shibpur	India	amit.rs2017@geology.iiests.ac.in
22	Sudhir Kumar Singh	Nehru Science Centre, University of Allahabad	India	sudhirinjnu@gmail.com
23	Allison Aldous	The Nature Conservancy	USA	aaldous@tnc.org
24	Imran Ahmad	Debre tabore university	India	wonder_env@yahoo.com
25	Sebastian Zabłocki	University of Warsaw, Faculty of Geology	Poland	s.zablocki@uw.edu.pl
26	Shammy Puri	Practical Hydrogeology University of Birmingham	UK	ShammyPuri@aol.com

Nota: Los nombres de los investigadores son considerados solamente como referencia en esta Tesis, pero no se autoriza su publicación en otro medio.

Anexo 3. Mapas complementarios de los capítulos.

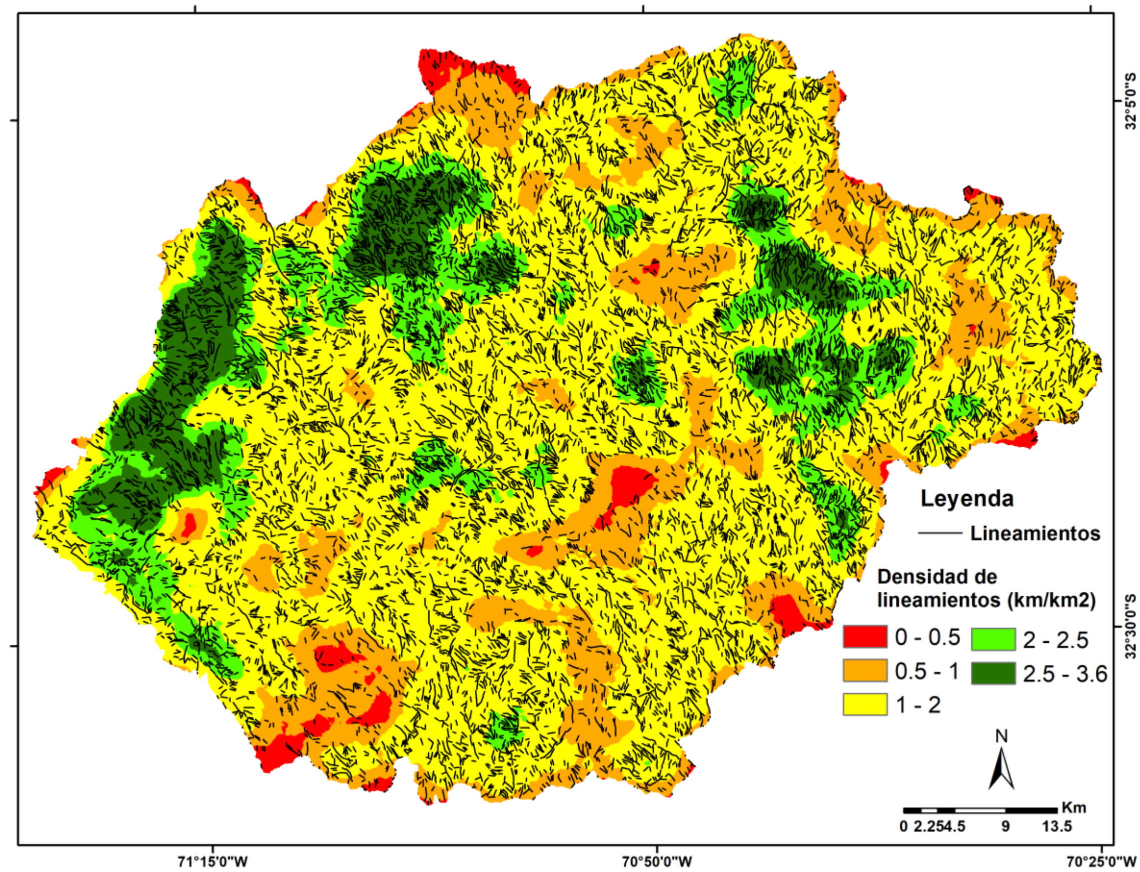

Figura 1. Mapa de lineamientos y densidad de lineamientos calculados como parte de la publicación 2 de esta Tesis.