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Cambio en el patrón espacial del paisaje y su efecto en los procesos hidrológicos. Hacia soluciones basadas en la naturaleza para la gestión de cuencas bajo un contexto de cambio climático.

(Changing spatial landscape patterns and their impact on hydrological processes: Toward nature-based solutions for watershed management under climate change)

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

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La Tesis de Doctorado en Ciencias Ambientales con Mención en Sistemas Acuáticos Continentales titulada “Cambio en el patrón espacial del paisaje y su efecto en los procesos hidrológicos. Hacia soluciones basadas en la naturaleza para la gestión de cuencas bajo un contexto de cambio climático”, de la Srta. Marieta Hernández Sosa y realizada bajo la Facultad de Ciencias Ambientales, Universidad de Concepción, ha sido aprobada por la siguiente Comisión de Evaluación:

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SIGLAS Y ABREVIATURAS

AET: Evapotranspiración real
CF: Factor Corrector
CR: Cultivos
CR2: Centro del Clima y la Resiliencia
ET: Evapotranspiración
GR: Pastizales
HP: Proceso Hidrológico
HPFI: Índice de Desempeño Hidrológico del Bosque
HU: Almacenamiento estático en la capa superior del suelo
IPCC: Panel Intergubernamental de Cambio Climático
KPs: Capacidad de pérdida del acuífero profundo
KP: Capacidad de percolación
Kps: Velocidad de flujo del acuífero profundo
KS: Capacidad de infiltración
Ksa: Conductividad hidráulica horizontal saturada
LUCC: Cambio de cobertura y uso de suelo
MASL: Metros sobre el nivel del mar
MDT: Modelo digital del terreno
MP: Plantaciones adultas
NBS: Soluciones basadas en la Naturaleza
NF: Bosques nativos
NSE: Índice de Eficiencia de Nash-Sutcliffe
PBIAS: Sesgo porcentual
PCC: Correlación de Pearson
PET: Evapotranspiración potencial
PLSR: Regresión de mínimos cuadrados parciales
RCP: Trayectorias Representativas de Concentración
RMSE: Raíz del error cuadrático medio
RSR: Índice de error estandarizado
SC: Matorrales
SF: Caudal
SPI: Índice de Precipitación Estandarizado
SWAT: Herramienta de Evaluación de Suelo y Agua
SWC: Características de Agua del Suelo
VIP: Importancia de la Variable en la Proyección
YP: Plantaciones jóvenes

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RESUMEN

El cambio climático es uno de los principales impulsores de los cambios en el ciclo hidrológico. En muchas regiones del mundo la disminución considerable de las precipitaciones y el aumento de las temperaturas extremas ha repercutido en la disminución del caudal y cambios en diversos procesos hidrológicos, como almacenamiento en la cubierta vegetal, infiltración y evapotranspiración. Sin embargo, numerosas investigaciones han demostrado como los cambios de cobertura y uso del suelo afectan también importantes componentes hidrológicos como régimen de sedimento, alteraciones de la calidad del agua y las afectaciones a la zona ribereña. Sin embargo, aún existen grandes contradicciones en torno a como los cambios del paisaje influyen en el ciclo del agua, fundamentalmente asociada con la inclusión de especies forestales exóticas y la pérdida de la superficie de bosques nativo. Algunos autores aseguran que la inclusión de las plantaciones forestales ejerce un rol estabilizador en los procesos hidrológicos, mientras que otros aseguran que la pérdida de bosques nativos repercute en la estabilidad y capacidad de regulación de las cuencas. Chile no se encuentra ajena a esta problemática, pues tanto el cambio climático como el desordenado aumento de las actividades económicas urbano-forestal están llevando a fuertes cambios en los componentes del ciclo del agua en numerosas cuencas del territorio. Esta problemática se agrava especialmente en la región centro y sur del país, donde se proyecta una disminución considerable de las precipitaciones en el futuro. Numerosas cuencas están siendo fuertemente intervenidas para el desarrollo de plantaciones forestales, lo que implica la ocupación de grandes extensiones de superficie nativa. Es por ello que, *el objetivo principal de esta investigación es evaluar los efectos de la configuración y composición del paisaje sobre componentes del ciclo del agua en las cuencas Quino y Muco del centro sur de Chile.*

El modelo hidrológico distribuido TETIS se implementó con el propósito de analizar cómo la combinación de dos principales forzantes el cambio climático y las transformaciones en la composición y configuración del paisaje afecta la respuesta hidrológica de las cuencas. El análisis se llevó a cabo tanto para el período histórico (1980–2018) como para proyecciones futuras (2030–2060 y 2061–2091). Los cambios en la cobertura y uso del suelo fueron analizados en dos etapas. En la primera, se utilizaron cuatro clasificaciones temporales (1986,

2001, 2011 y 2017) para caracterizar la evolución del paisaje. A partir de estas, y mediante el software *Fragstats*, se obtuvieron métricas espaciales que permitieron describir los patrones del paisaje y su influencia sobre los componentes del ciclo hidrológico. En la segunda etapa, se generaron cinco escenarios futuros de LUCC a partir del año 2017, construidos bajo criterios ambientales, sociales y económicos. Estos escenarios se combinaron con proyecciones climáticas para evaluar su impacto conjunto sobre los procesos hidrológicos.

Los resultados, obtenidos a través de análisis de correlación y regresión de mínimos cuadrados parciales (PLSR), indican que paisajes con mayor diversidad, fragmentación y menor conectividad espacial tienden a alterar significativamente la dinámica hidrológica. En particular, un paisaje altamente fragmentado afecta negativamente los flujos horizontales y verticales del agua. Asimismo, la expansión de plantaciones forestales en patrones agregados modifica los procesos verticales, como la infiltración y la evapotranspiración. La pérdida de contigüidad espacial de los bosques nativos, junto con la reducción en el número de parches, se asocia directamente con una disminución de procesos hidrológicos y en los caudales generados. Adicionalmente, los escenarios de LUCC simulados bajo el escenario climático RCP 8.5 revelan que el aumento en la superficie boscosa incrementa la evapotranspiración real en aproximadamente +20 mm. Este efecto es particularmente pronunciado en los escenarios que consideran recuperación mediante plantaciones forestales, con aumentos entre +30 y +40 mm. Por otro lado, los escenarios que promueven la reforestación con especies nativas muestran una mayor capacidad de retención hídrica en el sistema, especialmente durante períodos secos.

ABSTRACT

Climate change is one of the primary drivers of alterations in the hydrological cycle. In many regions worldwide, a significant decrease in precipitation combined with rising extreme temperatures has led to reduced streamflow and disruptions in key hydrological processes such as vegetation canopy storage, infiltration, and evapotranspiration. However, numerous studies have also demonstrated that land use and land cover changes (LUCC) significantly affect hydrological components such as sediment regimes, water quality, and riparian zone dynamics. Despite these findings, considerable controversy remains regarding how landscape

changes influence the water cycle, particularly in relation to the introduction of exotic forest species and the loss of native forest cover. Some authors argue that forest plantations play a stabilizing role in hydrological processes, while others contend that the loss of native forests compromises watershed stability and regulatory capacity. Chile is not exempt from this issue. Both climate change and the unregulated expansion of urban and forestry economic activities are driving significant alterations in hydrological components across numerous watersheds. This situation is particularly critical in the central-southern region of the country, where a substantial decrease in precipitation is projected for the future. Many catchments in this region are undergoing intense land transformation due to the expansion of forest plantations, often at the expense of native forest ecosystems. In this context, ***the primary objective of this study is to evaluate the effects of landscape composition and configuration on hydrological cycle components in the Quino and Muco catchments in south-central Chile.***

The distributed hydrological model TETIS was implemented to analyze how the combined influence of climate change and landscape transformation affects watershed hydrological responses. The analysis covers both historical conditions (1980–2018) and future projections (2030–2060 and 2061–2091). LUCC was assessed in two stages. First, four land cover classifications (1986, 2001, 2011, and 2017) were used to characterize landscape evolution. Spatial metrics were derived using the *Fragstats* software to quantify landscape patterns and their influence on hydrological components. Second, five future LUCC scenarios were generated from the 2017 baseline, based on environmental, social, and economic criteria. These were combined with climate projections to evaluate their joint impact on the water cycle. Results obtained through correlation analyses and partial least squares regression (PLSR) indicate that landscapes with higher diversity, greater fragmentation, and reduced spatial connectivity tend to significantly disrupt hydrological dynamics. Highly fragmented landscapes negatively affect both horizontal and vertical water fluxes. Furthermore, the expansion of forest plantations in aggregated spatial patterns alters vertical hydrological processes such as infiltration and evapotranspiration. The reduction in spatial contiguity of native forests, along with a decrease in the number of patches, is directly associated with diminished hydrological functioning and reduced streamflow.

Additionally, LUCC scenarios simulated under the RCP 8.5 climate projection reveal that increasing forested area leads to an approximate rise of +20 mm in actual evapotranspiration. This effect is particularly marked in scenarios involving recovery through forest plantations, with increases ranging from +30 to +40 mm. In contrast, scenarios promoting reforestation with native species show greater water retention capacity in the system, particularly during dry periods, highlighting their relevance as an adaptive strategy for hydrological regulation under climate change.

INTRODUCCIÓN

Los servicios ecosistémicos desempeñan un rol esencial en el bienestar humano al proveer alimentos, agua limpia, regulación de enfermedades, regulación del clima, polinización de cultivos, formación de suelos, beneficios culturales, entre otros. Se estima que el valor económico global de estos servicios alcanza los 125 billones de dólares anuales (FAO, 2020). Sin embargo, pese a su importancia, estos servicios no reciben la atención adecuada en las políticas públicas ni en los marcos normativos económicos, lo que se traduce en una insuficiente inversión en su protección y ordenamiento territorial.

Esta desconexión entre el desarrollo económico y la gestión de los servicios ecosistémicos tiene consecuencias visibles en el deterioro de los ecosistemas de agua dulce, cuyos niveles de disponibilidad y calidad se han visto seriamente comprometidos (Ochoa-Tocachi et al., 2016). Si bien el cambio climático constituye uno de los principales factores que amenazan los recursos hídricos con una marcada reducción en las precipitaciones, la transformación del paisaje sin una planificación territorial adecuada también intensifica esta problemática (Yohannes et al., 2021). Por ejemplo, la Fundación Nueva Cultura del Agua subraya que los ecosistemas acuáticos, cuando se mantienen en buen estado, no solo garantizan el suministro de agua, sino que también ofrecen múltiples servicios asociados. Sin embargo, su conservación depende directamente de un uso responsable, que asegure el mantenimiento de volúmenes mínimos de agua en los ecosistemas.

Chile no está ajeno a esta crisis. De acuerdo con el Cuarto Reporte del Medio Ambiente, en los últimos 63 años el país ha enfrentado una disminución significativa de las precipitaciones, especialmente en las regiones centro y sur. Los escenarios proyectados de cambio climático anticipan una reducción de hasta un 40% en las precipitaciones en estas zonas (CR2), lo que representa una amenaza directa a los recursos hídricos (Araya-Osses et al., 2020a; Vásquez et al., 2025). A esta situación se suma un proceso de transformación territorial ocurrido en las últimas décadas: en los últimos 40 años, la zona centro-sur ha experimentado una sustitución masiva de bosques nativos por plantaciones forestales tales como *Pinus radiata* y *Eucalipto globulus* (Huber et al., 2010b). Esta pérdida de cobertura nativa no solo representa una amenaza a la biodiversidad, sino que también afecta gravemente el ciclo hidrológico,

alterando procesos fundamentales como la infiltración, la evapotranspiración y la regulación del caudal base (Martínez-Retureta et al., 2020; Yohannes et al., 2021). En este contexto, se hace evidente la necesidad de repensar las políticas de ordenamiento territorial y gestión de recursos naturales, integrando una mirada ecosistémica que reconozca el valor funcional de la cobertura nativa en la regulación hídrica y la resiliencia frente al cambio climático.

I.1. Implicaciones del cambio climático en el ciclo del agua a nivel de cuencas.

El calentamiento en el sistema climático es inequívoco, la atmósfera y el océano se han calentado, los volúmenes de nieve y hielo han disminuido y el nivel del mar se ha elevado. La evidencia más sólida y completa de los impactos observados del cambio climático corresponde a los sistemas naturales. En muchas regiones, los cambios en el régimen de precipitación o el derretimiento de nieve y hielo han alterado los sistemas hidrológicos, lo que afecta a los recursos hídricos en términos de cantidad y calidad del agua (IPCC 2014). Es indiscutible que las actividades humanas, especialmente la quema de combustibles fósiles, han causado un calentamiento global de aproximadamente 1,1 °C entre 1850 y 2020. Cada aumento adicional en la temperatura global intensifica los riesgos para los ecosistemas y las sociedades humanas, incluyendo fenómenos extremos más frecuentes y severos. Lamentablemente las comunidades y ecosistemas más vulnerables, que han contribuido menos al cambio climático, son los más afectados por sus consecuencias (IPCC 2023). Las presiones adicionales del cambio climático sobre los recursos naturales son particularmente evidentes en zonas con estrés hídrico y están generando desafíos adicionales relacionados con la gestión, la disponibilidad y la conservación del agua. La adaptación a las nuevas condiciones climáticas y socioeconómicas requiere soluciones innovadoras con un impacto mínimo en los recursos y ecosistemas ya estresados (Apostolaki, 2025). Comprender las variaciones y los mecanismos que impulsan los recursos hídricos a partir de los cambios del clima es esencial para la gestión y planificación eficaces de este importante recurso (Y. Liu et al., 2025).

Diversos estudios a nivel internacional han demostrado que el cambio climático tiene impactos significativos sobre los componentes del ciclo hidrológico. Asociado a la escasez hídrica, se han integrado proyecciones climáticas con componentes socioeconómicos,

considerando las necesidades ambientales (caudales ecológicos), para evaluar tanto calidad como cantidad de agua (Tong et al., 2024). Por otra parte, se ha integrado clima, sociedad y escasez de agua en zonas vulnerables como Medio Oriente y norte de África. Demostrando como el cambio climático agrava la escasez e incrementa las tensiones geopolíticas y sociales (Mfarrej, 2025). En Irán occidental, se analizó los factores socio-psicológicos que influyen en cómo los agricultores se adaptan a la escasez de agua. Demostrando como muchas veces la principal variable no es el conocimiento de la escasez si no el deseo de cambiar hacia nuevas técnicas (Azadi et al., 2025). Particularmente los efectos del cambio climático sobre algunos componentes del ciclo del agua se esperan tengan impactos considerables en algunas regiones del mundo. Por ejemplo, en Marruecos mediante la combinación de simulaciones hidrológicas y proyecciones climáticas, se han observado reducciones considerables en el caudal proyectado bajo escenarios de disminución de precipitación y aumento de temperatura, en cuencas del norte de África, cercanas al Mar de Alborán (Giustarini et al., 2023). En el río Harvey en Australia mediante el uso de herramientas automáticas y objetivas se logró descomponer el caudal en sus componentes rápido (fastflow) y lento (slowflow), para detectar como los cambios estacionales y de largo plazo afectan procesos como la infiltración, vinculándolos con posibles efectos del cambio climático (Lyne, 2025). En cuencas de regiones frías de Canadá, donde el régimen hídrico depende fuertemente del deshielo y de la precipitación sobre nieve, se utilizó el modelo atmosférico WRF junto con el modelo hidrológico MESH. Incorporando un conjunto de 15 simulaciones del modelo climático regional CanRCM4. Este enfoque permitió concluir que la variabilidad interna del clima, agravada por el cambio climático tiene una influencia considerable sobre el comportamiento futuro del caudal, incrementando el riesgo de eventos extremos en cuencas de la provincia de Alberta (Rajulapati et al., 2024). Sin embargo, no todos los escenarios proyectados indican un deterioro de los componentes del ciclo del agua. En algunas regiones, como Pakistán, simulaciones aplicadas a la cuenca del río HUB sugieren un aumento de caudales promedio, lo que implicaría una posible reducción en la escasez de agua a futuro (Aslam et al., 2024). De forma similar, en la India, el uso de modelos basados en aprendizaje profundo como LSTM (Long Short-Term Memory), entrenados con datos históricos y proyecciones futuras bajo escenarios RCP, ha permitido anticipar aumentos significativos del caudal durante la

temporada de monzones, como resultado de temperaturas más altas y mayor precipitación bajo escenarios de altas emisiones (Sarkar et al., 2025).

En el contexto del cambio climático, múltiples estudios han abordado la dinámica de la evapotranspiración (ET), reconociéndola como un componente crítico del balance hídrico. La evidencia empírica indica que tanto la evapotranspiración real (AET) como la potencial (PET) se ven afectadas por factores climáticos, fisiológicos y de cobertura del suelo, generando impactos diferenciados a escala regional. En la cuenca del río North Saskatchewan (Canadá), se aplicó un modelo hidrológico integrado para evaluar la AET y sus fuentes en distintos escenarios climáticos. Se identificó que la mayor parte de la AET proviene de la transpiración vegetal y evaporación subsuperficial, y se proyecta un aumento sostenido de esta variable, particularmente en áreas montañosas. Esto genera un riesgo creciente de agotamiento de aguas subterráneas en zonas de llanura, debido a una mayor demanda hídrica (Serrano Diaz et al., 2024). En el alto Nilo Azul, se analizó la respuesta de la PET y del índice de aridez (AI) ante escenarios de altas emisiones (RCP) mediante seis modelos climáticos globales. Se utilizaron los métodos de Penman-Monteith y Hargreaves, siendo este último más eficiente. Los resultados proyectan un incremento sostenido de la PET y del AI, especialmente durante la estación seca, lo que implica una mayor escasez de humedad asociada al aumento de la temperatura (Gismu Chakilu et al., 2024). En el noreste de China, una región caracterizada por la escasez hídrica, se evaluaron los efectos del cambio climático y del reverdecimiento de la vegetación sobre la evapotranspiración y la escurrentía (WY). Los resultados indican que, a partir de 1999, la ET mostró una tendencia creciente, mientras que la WY disminuyó (Ren et al., 2024). Por otra parte en el caso específico de Chile, se proyectó el cambio climático bajo el escenario de altas emisiones SSP5-8.5, a partir de salidas diarias de modelos climáticos globales del conjunto CMIP6, que fueron sometidas a un proceso de downscaling estadístico y corrección de sesgo. El estudio mostró que la mayor parte del territorio experimentará un aumento de la aridez hacia finales del siglo XXI, con una disminución de hasta un 40% en la precipitación anual en muchas regiones, a excepción de la Patagonia (al sur de 50°S), donde este descenso no sería tan marcado. Además, se proyecta una reducción significativa en la acumulación de nieve en los Andes extratropicales, con pérdidas de hasta un 80%, especialmente en cuencas del norte como Salado y Limarí. Esta disminución se explica por la

menor precipitación anual y el aumento del nivel de congelación, que favorece lluvias en lugar de nevadas (Vásquez et al., 2025).

En términos generales, estas investigaciones confirman que el cambio climático no tiene efectos homogéneos: mientras algunas regiones enfrentan reducciones en el caudal y aumento de la evapotranspiración, lo que agrava la escasez de agua, otras podrían experimentar aumentos temporales del caudal, aunque acompañados por una mayor variabilidad e incertidumbre hídrica futura. Por ejemplo, se observa una tendencia general a la disminución del caudal en regiones donde la precipitación disminuye y las temperaturas aumentan, como en el norte de África. En contraste, algunas regiones de Asia, como Pakistán e India, podrían experimentar aumentos en el caudal, especialmente durante la temporada de monzones, debido a mayores temperaturas y precipitaciones proyectadas bajo escenarios de altas emisiones. Lo que sí es consistente en casi todos los estudios es la necesidad de abordar esta problemática mediante soluciones sostenibles que adopten enfoques multisectoriales, integrando la gobernanza, la tecnología, el medio ambiente y la sociedad. Se enfatiza la necesidad de iniciativas colaborativas y una planificación que considere la heterogeneidad del clima y la vegetación, especialmente en zonas áridas. Entre las estrategias sugeridas, destaca la conservación de agua y la mejora de la recarga subterránea durante las temporadas lluviosas como medidas clave de adaptación. Si bien estas investigaciones han demostrado el cambio climático es uno de los principales impulsores de los cambios en el ciclo del agua, esta perspectiva ha sido matizada en investigaciones más recientes, específicamente en regiones donde las actividades humanas son frecuentes e intensivas.

I.2. Las modificaciones del paisaje natural y escenarios futuros de cambio de cobertura y uso de suelo. Efectos en las cuencas hidrográficas.

El cambio de cobertura y uso del suelo ha sido identificado como uno de los principales impulsores antropogénico que más afecta los ecosistemas naturales y la provisión de servicios ecosistémicos (Bispo et al., 2023). Estudios recientes han demostrado que las modificaciones del paisaje, especialmente aquellas relacionadas con el cambio en el uso y la cobertura del suelo, tienen efectos profundos sobre los procesos hidrológicos a nivel de cuenca. La

expansión agrícola, forestal y urbana ha reducido áreas clave como humedales, incrementando significativamente la demanda hídrica y exacerbando la escasez de agua en muchas regiones (Lu et al., 2023). Estas transformaciones, cuando son gestionadas de forma inadecuada, alteran componentes esenciales del ciclo hidrológico, como la infiltración, la percolación, y la evapotranspiración (Martínez-Retureta et al., 2020).

Diversos estudios que han analizado la relación entre la explotación forestal y los componentes hidrológicos. Han demostrado que el aumento de esta actividad, que usualmente reemplaza superficies de bosque nativo y tierras agrícolas (Hernández et al., 2024), ha generado una disminución del caudal base y del caudal de estiaje en las cuencas intervenidas (Albaugh et al., 2013; Buytaert et al., 2007). Por otra parte, (Alvarez et al., 2013; Hurtado-Pidal et al., 2022, 2025) han demostrado como la pérdida de superficie de bosques nativos ha aumentado los procesos de escorrentía. Específicamente (Hurtado-Pidal et al., 2022) demostraron que es más importante respetar la ubicación del bosque nativo, que el grado de fragmentación, para ayudar a disminuir las inundaciones generadas por escorrentía. Mientras que, Julián et al. (2018), determinaron que las cuencas con mayor reducción de su capacidad de regulación estaban relacionadas con un aumento de las plantaciones forestales. En el caso de la evapotranspiración se encuentran estudios como el desarrollado en cuencas del norte de China, a través de la mejora del modelo Budyko-Fu, donde se ha logrado incorporar la dinámica de la vegetación mediante la producción primaria bruta (GPP), con el fin de estimar la evapotranspiración (ET) y analizar sus factores determinantes. Los resultados muestran que la ET aumenta, siendo el cambio en la vegetación el principal impulsor, seguido por el cambio en precipitación (Du et al., 2024).

Sin embargo, en contraste con los estudios que atribuyen un rol que puede tener las modificaciones del paisaje sobre los componentes del ciclo hidrológico, existe un grupo de investigaciones que cuestiona esta relación. Hawtree et al. (2015); Wine & Zou. (2012), sostienen que los cambios en el uso y cobertura del suelo no muestran efectos evidentes sobre el comportamiento hídrico. De manera similar Kurzweil et al. (2021) argumentan que la restauración de la vegetación nativa no necesariamente incrementa el caudal superficial. En el caso de Chile, Pizarro et al. (2005) plantearon que la expansión de plantaciones de *Pinus*

radiata en la cuenca del río Purapel podría generar pérdidas de agua; sin embargo, los resultados no evidenciaron variaciones hidrogeológicas significativas. Por otro lado, Renée Brooks et al. (2010) aseguran que las plantaciones forestales pueden desempeñar un rol estabilizador en el ciclo hidrológico, al equilibrar la relación entre precipitación, escorrentía superficial y recarga de acuíferos.

Ahora bien, el análisis de los efectos del paisaje sobre el ciclo del agua no debe limitarse únicamente a su composición. La configuración espacial, evaluada a través de métricas del paisaje, se ha consolidado como una herramienta fundamental para comprender cómo las modificaciones en la estructura territorial inciden en los distintos componentes del balance hídrico. Los patrones del paisaje proporcionan un marco integral para analizar la distribución e interconexión del flujo de agua a través de diferentes superficies terrestres y tipos de cobertura. Un principio fundamental de la ecología del paisaje es que los patrones espaciales están acoplados con los procesos y funciones ecológicas. La hidrología es uno de los principales impulsores de los procesos ecológicos, y la vegetación, en particular, influye fuertemente en la hidrología, generando retroalimentaciones (mediante obstrucción del flujo, gradientes de evaporación, cambios en la fricción del lecho y en el almacenamiento del agua) que, a su vez, pueden modificar la estructura y función del paisaje (Yuan et al., 2015). Varios estudios han demostrado la relación entre métricas del paisaje y cambios en los regímenes de erosión y sedimentación dentro de cuencas hidrográficas. Estas métricas incluyen el índice de diversidad de Shannon, el índice de agregación, el índice de parche más grande, el índice de contagio y el índice de cohesión de parches, entre otras (Da Silva et al., 2015; Shi et al., 2013). Además, investigaciones han destacado que paisajes bien conectados pueden mitigar eficazmente la erosión del suelo (Jiang et al., 2020). Otras métricas relacionadas con área, forma, interceptación y conectividad han demostrado influir en la escorrentía superficial, el caudal base y la dinámica de percolación (Boongaling et al., 2018; Frey et al., 2021).

Por otra parte, otra forma de comprender mejor el papel de las modificaciones del paisaje en la regulación del agua se ha recurrido a la simulación de escenarios futuros de LUCC, mediante modelos que permiten analizar causas y consecuencias ambientales y socioeconómicas. Uno de los modelos más utilizados es FLUS (Future Land Use Simulation),

el cual combina un enfoque de dinámica de sistemas (SD), que proyecta la demanda de uso del suelo a gran escala, con un modelo de autómatas celulares (CA) que representa la dinámica espacial desde una perspectiva de abajo hacia arriba (C. Liu et al., 2017). Este modelo ha demostrado que la expansión urbana y minera reduce el espacio ecológico, aumenta las emisiones de carbono y degrada la calidad del hábitat (Feng et al., 2025). La versión mejorada FLUS-3D ha sido útil para simular dinámicas urbanas bajo distintos escenarios socioeconómicos (SSPs) y ha sido aplicada en estudios de mitigación del cambio climático urbano (Xu et al., 2024). Otro modelo destacado es PLUS, basado también en autómatas celulares y datos ráster. Su ventaja radica en su alta precisión y velocidad de simulación, así como en su capacidad para representar dinámicas no lineales del cambio de uso de suelo en intervalos de tiempo específicos (Liang et al., 2021). Mediante PLUS, se ha explorado la relación entre el desarrollo urbano y variables como el almacenamiento de carbono, la erosión del suelo y la calidad del hábitat (Hou et al., 2025; D. Ma et al., 2025; Tian et al., 2025; Wu & Wang, 2025; Zhang et al., 2025).

Además de los modelos computacionales, algunos estudios han utilizado el juicio experto y talleres participativos para construir escenarios de LUCC. Por ejemplo, Martínez-Harms et al. (2017) evaluaron los impactos del cambio climático, la urbanización y los incendios sobre los servicios ecosistémicos en Chile central. Igualmente, Zhao et al. (2025) usaron encuestas para simular restauración de tierras agrícolas, mientras que Pelorosso et al. (2025) analizaron el efecto de dos escenarios contrastantes (renaturalización vs. expansión urbana) en la conectividad del paisaje bioenergético. Steward et al. (2025) siguieron un enfoque participativo de cuatro etapas para definir trayectorias de desarrollo territorial. Si bien muchos de estos modelos permiten, visualizar impactos futuros del uso del suelo bajo diferentes trayectorias, integran factores humanos y naturales. La mayoría de los estudios se enfocan en expansión urbana y no abordan con suficiente profundidad la restauración forestal a gran escala. Mostrando poca evidencia sobre sus implicaciones hidrológicas, especialmente en relación con servicios de regulación y aprovisionamiento de agua, en el contexto del cambio climático y la seguridad hídrica. Dado el creciente desafío que representa el cambio climático y la crisis hídrica global, se vuelve urgente desarrollar estudios que integren métricas de paisaje, escenarios de cobertura de uso de suelo con enfoque sustentable y análisis

hidrológicos robustos, enfocados en proyectar una planificación territorial basada en restauración ecológica y su capacidad de contribuir a la seguridad hídrica y la resiliencia de los ecosistemas.

I.3. La modelación hidrológica como herramienta integradora para evaluar los efectos sinérgicos del cambio climático y del cambio en el uso y cobertura del suelo sobre los servicios ecosistémicos.

El cambio climático y las transformaciones en el uso del suelo generan impactos profundos sobre los recursos hídricos, afectando tanto su disponibilidad como su calidad. Para anticiparse a estos efectos y planificar adecuadamente, es imprescindible desarrollar proyecciones que, aunque conllevan cierto grado de incertidumbre, permiten fundamentar decisiones informadas en la gestión del agua y en el diseño de políticas públicas. Si bien existen múltiples escenarios climáticos a escala global y regional, su verdadero valor radica en la capacidad de traducirlos en implicancias concretas para la hidrología y la calidad del agua. En este contexto, los modelos hidrológicos se convierten en herramientas clave para comprender, simular y proyectar los efectos de estos cambios sobre el ciclo hidrológico y los servicios ecosistémicos asociados (Keller et al., 2023).

Existen numerosos estudios que han establecido la relación combinada entre los cambios de cobertura y uso del suelo con los componentes del ciclo hidrológico, fundamentalmente mediante modelos hidrológicos unidimensionales o semi-distribuidos (Chen et al., 2024; Haas et al., 2022; H. Ma et al., 2023). En este contexto, el modelo SWAT se ha consolidado como una herramienta ampliamente utilizada. Mediante el uso de este modelo se ha logrado simular adecuadamente eventos de inundación, especialmente con una resolución horaria, en la parte alta del río Weihe, en China. Demostrando como la expansión de tierras agrícolas aumenta significativamente el escurrimiento, mientras que el incremento de la cobertura vegetal (bosques y pastizales) lo reduce ligeramente, dejando los efectos del cambio climático como secundarios (Y. Liu et al., 2022). De manera complementaria, en una cuenca semiárida del oeste de India, el modelo también fue utilizado para simular el caudal considerando ambas forzantes, demostrando que, si bien ambos factores influyen, el cambio climático representa

el principal impulsor en el caudal (Sharma et al., 2022). Específicamente en Chile, en los ríos Andalien, Quino y Muco de la región centro-sur de Chile, se ha logrado implementar el modelo SWAT para combinar los efectos del clima histórico y futuro y los cambios de cobertura y uso de suelo en la respuesta hidrológica de estas cuencas (Martínez-Retureta et al., 2020). Logrando determinar que el modelo SWAT es eficaz para evaluar los efectos de los LUCC sobre la hidrología en cuencas costeras del centro-sur de Chile, a partir del clima actual y futuro. Esta investigación demostró como el reemplazo de los bosques nativos por plantaciones exóticas provoca un incremento en la evapotranspiración y escorrentía superficial. Mientras que, a futuro, las cuencas experimentarían una disminución en la percolación, escorrentía y flujo subterráneo.

Por otra parte, el modelo hidrológico TETIS es un modelo distribuido espacialmente con parámetros físicos que simula los componentes principales de la fase terrestre del ciclo hidrológico mediante una malla regular (Francés et al., 2007). Se ha implementado en regiones montañosas caracterizadas por climas húmedos a escalas diarias (Peña et al., 2016) y subdiarias (Hurtado-Pidal et al., 2022, 2025), así como en entornos mediterráneos y regiones montañosas de media y alta altitud, similares a la zona de estudio considerada (Francés et al., 2007; Gomis-Cebolla et al., 2022). Se ha utilizado como una alternativa eficiente y simplificada para modelar ciclos de carbono y nitrógeno en ecosistemas forestales semiáridos de la región Mediterránea (Puertes et al., 2019, 2020). Por otra parte, se ha utilizado, para evaluar cómo diferentes patrones espaciales de deforestación del bosque nativo afectan el riesgo de inundaciones, especialmente en eventos de tormenta pequeños y moderados, en una cuenca húmeda tropical de la Amazonía ecuatoriana (Hurtado-Pidal et al., 2022).

Ante esta disyuntiva, surge la pregunta sobre qué tipo de simulación es más adecuada: ¿distribuida o semidistribuida? Aunque no específicamente se establece la relación SWAT-TETIS, se logra apreciar algunas diferencias entre modelos. En la cuenca del río Tamakoshi (TRB), en Nepal, se comparó el desempeño entre tres modelos (SPHY, HBV y HEC-HMS). El modelo SPHY (distribuido) tiene mejor desempeño en la calibración, mientras que los modelos HBV y HEC-HMS (semi-distribuidos) logran funcionar mejor en la fase de validación. Destacando que tanto modelos distribuidos como semi-distribuidos pueden ser

útiles, pero su elección debe basarse en el objetivo del estudio y la disponibilidad de datos (Budhathoki et al., 2025). Por otra parte, un estudio realizó una evaluación comparativa de 21 modelos hidrológicos y de calidad del agua utilizados para simular los efectos del cambio climático y del uso del suelo en recursos hídricos. Si bien SWAT destaca por su facilidad de uso, capacidad para integrar cambios de uso del suelo y clima en una sola simulación. Los modelos distribuidos MIKE-SHE y MODHMS tienen una representación espacial más detallada y continua del sistema hidrológico (Keller et al., 2023). Esto evidencia que, para establecer la relación más precisa entre los componentes del ciclo del agua y la dinámica espacio-temporal del paisaje, resulta necesario recurrir a una modelación distribuida. Este enfoque permite capturar, a nivel de píxel, los procesos hidrológicos que ocurren en cada tipo de uso del suelo y en cada ubicación específica del territorio, proporcionando así una comprensión más detallada y realista del comportamiento hidrológico del sistema.

La modelación hidrológica es una herramienta esencial para analizar los efectos sinérgicos del cambio climático y de las transformaciones en el uso y cobertura del suelo sobre los servicios ecosistémicos hídricos. Modelos como SWAT han sido ampliamente utilizados gracias a su facilidad de implementación, su capacidad para integrar múltiples escenarios y su sólido respaldo técnico. Sin embargo, presentan ciertas limitaciones en la representación espacial detallada del ciclo hidrológico, lo que puede restringir su utilidad en estudios que requieren un análisis más localizado y preciso. En contraste, el modelo TETIS, al ser distribuido y basado en parámetros físicos, permite una representación más fiel de la dinámica espacial y temporal del agua, especialmente en cuencas con condiciones complejas o en regiones climáticamente variables, como las zonas semiáridas o húmedas tropicales. Por estas razones, TETIS se presenta como una alternativa más adecuada para abordar el objetivo general de esta investigación.

I.4. Proyección de escenarios de uso y cobertura del suelo integrando Soluciones basadas en la Naturaleza (SbN) como estrategia sostenible frente al cambio climático.

La Unión Internacional para la Conservación de la Naturaleza (UICN) define las Soluciones basadas en la Naturaleza (SbN) como: *Acciones destinadas a proteger, gestionar de manera sostenible y restaurar ecosistemas naturales o modificados, con el fin de enfrentar desafíos*

sociales de forma eficaz y adaptativa, al tiempo que se generan beneficios tanto para el bienestar humano como para la biodiversidad. Estas soluciones no actúan de manera aislada, sino que a menudo se implementan en conjunto con otros tipos de intervenciones. Según la UNESCO 2018, las soluciones basadas en la naturaleza (SbN) *están inspiradas y respaldadas por la naturaleza y utilizan o imitan los procesos naturales para contribuir a la gestión mejorada del agua.* Una solución basada en la naturaleza puede implicar la conservación o rehabilitación de los ecosistemas naturales y/o la mejora o creación de procesos naturales en ecosistemas modificados o artificiales, se pueden aplicar a microescala o a macroescala. Las soluciones basadas en la naturaleza (SbN) ofrecen un enfoque eficaz para mitigar los impactos del cambio climático sobre los recursos hídricos. Estas soluciones, que incluyen la protección, gestión sostenible y restauración de ecosistemas como bosques y humedales, desempeñan un papel crucial en la regulación del ciclo del agua.

Existen diversas investigaciones que han integrado las soluciones basadas en la naturaleza, para integrarlas en gestión de cuenca y planificación del territorio. En las cuencas del norte y centro de los estados más al este de los Estados Unidos. Se demostró como la restauración y conservación de los bosques nativos puede mejorar la infiltración, recargar acuíferos y reducir la escorrentía superficial, lo que ayuda a mantener los caudales base en épocas secas y a mitigar inundaciones invernales. Demostrando como la conservación continua de esta superficie es esencial para conservar los servicios hidrológicos (Botero-Acosta et al., 2022). En las cuencas de Gefersa y Legedadi en Etiopía, se construyeron escenarios futuros de uso del suelo a partir de imágenes satelitales Landsat (2012 y 2022) y técnicas de aprendizaje automático. Para evaluar los efectos sobre el balance hídrico y la producción de sedimentos. Aunque no se modelaron escenarios SbN de forma directa, el estudio destaca el potencial de las SbN para mitigar los efectos negativos del cambio de uso del suelo y del clima (Bayissa et al., 2025).

Otra forma eficaz de implementar las (SbN) es la recuperación de los humedales, ya que ayudan a almacenar agua y reducir el riesgo de inundaciones. En climas monzónicos esta implementación pudiera ser contradictoria, ya que con grandes picos de precipitaciones los humedales se pueden volverse insuficientes. Sin embargo, en el río Brahmaputra, en la India

se estableció un enfoque hidroecológico, donde se liberaba agua en los humedales considerando ciertos niveles de precipitación y las necesidades ecológicas del ecosistema. Demostrando el potencial de estas SbN para reducir el riesgo de inundaciones (Gupta et al., 2024). Otra investigación, que considera los impactos de la inundación y la implementación de las SbN para contrarrestarlo es el de un río en África subsahariana, donde la expansión descontrolada y el cambio climático agravan los riesgos. Se centró en el área metropolitana de Kumasi (Ghana). Demostrando como la más eficaz e integral es la restauración combinada de riberas y humedales, para reducir los picos de caudal (Enu et al., 2025). Aunque las NbS han sido ampliamente estudiadas frente a otros desastres como las inundaciones, su evaluación frente a la escasez de agua ha sido menos abordado. Estifanos (Yimer et al., 2024), realizaron una revisión crítica y sistemática de la literatura sobre NbS aplicadas a la mitigación de sequías a nivel global, Europa y Bélgica. Identificando un vacío importante en la investigación. Por otra parte, en el caso de Chile, a partir de una exhaustiva revisión bibliográfica, se muestra cuáles son las mejores prácticas de SbN para enfrentar conflictos de escasez hídrica en la Ecorregión Mediterránea. Se propone la restauración de cuencas y humedales mediante la reforestación, revegetación, conservación de ecosistemas y protección de franjas ribereñas. Estas acciones permiten regular el ciclo hidrológico, mejorar la infiltración de agua, reducir la erosión y aumentar tanto la cantidad como la calidad del agua disponible (Schneider-Valenzuela et al., 2023).

Estas investigaciones, junto con las estrategias promovidas por las guías internacionales de Soluciones basadas en la Naturaleza (SbN), evidencian que la restauración, la reforestación y la conservación de ecosistemas de bosque pueden contribuir significativamente a la recuperación de los servicios ecosistémicos a nivel de cuenca hidrográfica. Esto es especialmente relevante en contextos de escasez hídrica y cambio climático, ya que estas acciones favorecen una gestión regional más eficaz del recurso hídrico, regulando los flujos de agua y contribuyendo al equilibrio del ciclo hidrológico. Sin embargo, aún existe escasa evidencia científica que demuestre con precisión cómo la restauración y conservación de bosques nativos logra amortiguar los efectos del cambio climático sobre los distintos componentes del ciclo del agua. Aunque se reconoce que la vegetación funciona como una esponja natural almacenando agua durante los eventos de lluvia y liberándola gradualmente

en períodos secos, estabilizando así los flujos hídricos y reduciendo la escorrentía superficial, son muy pocos los estudios que simulan estos procesos en escenarios de recuperación de bosque nativo y evalúan su impacto real sobre el balance hídrico. Por ello, modelar escenarios futuros de uso del suelo basados en SbN, como la restauración de bosques nativos frente a la expansión de plantaciones forestales exóticas, representa una estrategia clave para demostrar su efectividad en la sostenibilidad de la disponibilidad hídrica a largo plazo, así como para promover una gestión más resiliente frente al estrés hídrico.

CAPÍTULO II. HIPÓTESIS Y OBJETIVOS ESPECÍFICOS

II.1. Planteamiento del problema y novedad científica:

En las últimas décadas, el cambio climático y la transformación acelerada y desregulada del paisaje han provocado alteraciones significativas en la estructura y función de los ecosistemas a escala de cuenca hidrográfica. Factores como la disminución sostenida de las precipitaciones, el aumento de las temperaturas y la expansión homogénea de usos del suelo intensivos como sistemas agrícolas y plantaciones forestales han reemplazado ecosistemas nativos clave, como bosques, matorrales y pastizales. Esta transformación ha generado

impactos directos sobre procesos hidrológicos fundamentales, incluyendo la infiltración, la retención de humedad, la evapotranspiración y el escurrimiento superficial.

Asimismo, la fragmentación del paisaje y la pérdida de continuidad en la cobertura vegetal han disminuido la capacidad de los ecosistemas para regular el flujo hídrico, afectando negativamente la resiliencia de los sistemas fluviales frente a perturbaciones climáticas. Esta situación es especialmente crítica en el centro-sur de Chile, donde se proyecta una fuerte reducción en las precipitaciones y un aumento de la presión sobre los ecosistemas debido a la expansión no regulada de plantaciones forestales, lo que ha resultado en la degradación del bosque nativo y una creciente pérdida del equilibrio hídrico en las cuencas.

Frente a este escenario, surge la necesidad urgente de comprender cómo el efecto combinado del clima, la configuración espacial del paisaje y su composición influyen sobre el ciclo del agua a escala de cuenca. En este contexto, resulta fundamental explorar enfoques que promuevan una gestión territorial más sostenible, siendo las Soluciones Basadas en la Naturaleza (SbN) una alternativa prometedora. Estas soluciones permiten integrar la conservación, restauración y uso sostenible de los ecosistemas para mejorar la regulación hídrica, incrementar la resiliencia climática y contribuir al bienestar humano, sin comprometer los servicios ecosistémicos clave.

Sin embargo, existe aún escasa evidencia científica que evalúe el impacto de las SbN sobre el funcionamiento hidrológico de las cuencas en condiciones de cambio climático y transformación del uso del suelo. Por tanto, se vuelve prioritario investigar cómo distintos escenarios de restauración ecológica, preservación de cobertura nativa y reconfiguración del paisaje, basados en SbN, pueden contribuir a mantener o mejorar el balance hídrico en cuencas vulnerables del centro-sur de Chile. ***Por tanto, el objetivo principal de esta investigación es evaluar los efectos de la configuración y composición del paisaje sobre componentes del ciclo del agua en dos cuencas del centro sur de Chile.***

II.2. Hipótesis

H1: Las modificaciones en la configuración del paisaje inducen cambios en la dinámica de procesos hidrológicos y el caudal, siendo estos efectos modulados fundamentalmente por la agregación de las coberturas forestales en diversas escalas espaciales.

H2: Los escenarios de restauración y preservación de bosque nativo, diseñados a partir de Soluciones Basadas en la Naturaleza, políticas ambientales vigentes y criterios socioeconómicos, permiten mantener una mayor disponibilidad de agua en el balance hídrico de cuencas del centro-sur de Chile, especialmente durante los períodos de mayor escasez hídrica.

II.3. Objetivo general: Evaluar los efectos de la configuración y composición del paisaje sobre componentes del ciclo del agua en dos cuencas del centro sur de Chile.

II.4. Objetivos específicos

OE1: Relacionar los patrones del paisaje con los procesos hidrológicos, de las últimas 4 décadas.

OE2: Determinar los patrones del paisaje que repercuten en el caudal, de las últimas 4 décadas.

OE3: Establecer los efectos de escenarios de patrón del paisaje bajo el enfoque de SBN y criterio socioeconómico, sobre el caudal y el balance de agua en un contexto de cambio climático.

CAPÍTULO III. MATERIAL Y MÉTODOS

III.1. Área de estudio

Las cuencas de los ríos Quino y Muco se encuentran en la IX Región de La Araucanía, en el sur de Chile, ubicadas entre las coordenadas geográficas 38° 00' 00" S, 72° 20' 00" O - 71° 45' 00" O, según el datum WGS84. La superficie de las cuencas del Quino y del Muco es de 301 y 649 kilómetros cuadrados, respectivamente. Las altitudes en estas cuencas varían entre 307 y 1714 metros sobre el nivel del mar (msnm) para el Quino, y entre 190 y 1453 msnm

para el Muco. El clima predominante es mediterráneo, con una transición gradual hacia un clima templado lluvioso en la parte alta de la cuenca del Quino. La temporada húmeda se extiende de abril a septiembre, mientras que el período seco ocurre entre octubre y marzo. La precipitación media anual varía entre 1800 y 1900 milímetros. La temperatura media anual es de aproximadamente 10,0 °C, registrándose las temperaturas más altas en los meses más secos y las más bajas en los meses más lluviosos. En la región predominan los suelos del orden Andisol, de textura franco-limosa, caracterizados por su profundidad, permeabilidad moderada y buen drenaje. La cobertura del uso de suelo del 2017 en ambas cuencas está compuesta principalmente por cultivos (27 %), bosque nativo (26 %), matorrales (17 %), plantaciones forestales (17 %), pastizales y suelos sin vegetación (11 %), áreas urbanas (0,34 %) y cuerpos de agua (0,03 %), como se muestra en la Figura 1. La cuenca del Quino presenta un mayor porcentaje de intervención de su territorio (55 %), mientras que la cuenca del Muco tiene un 39 %.

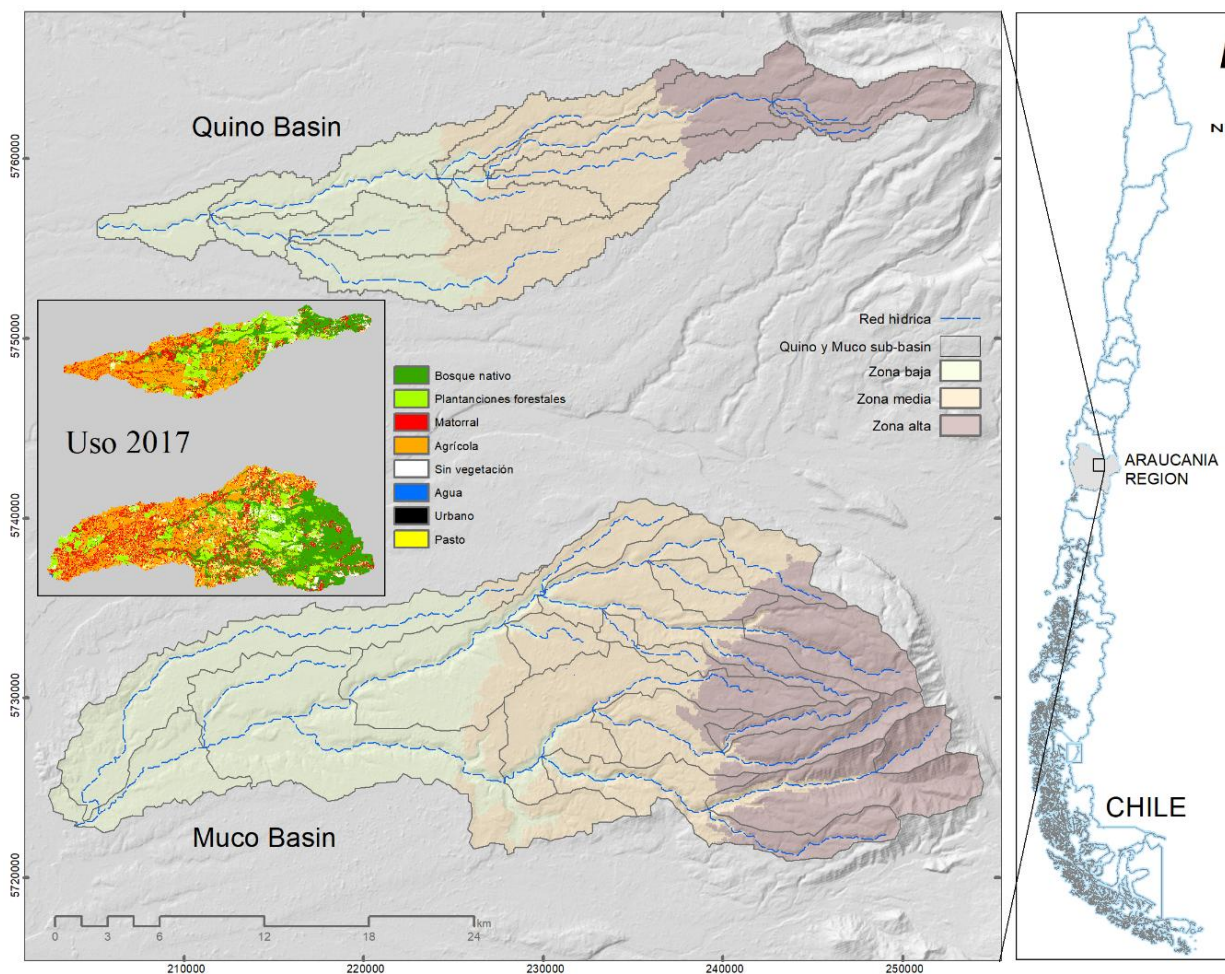


Figura 1. Ubicación área de estudio. Cuencas Quino y Muco. Cambio de cobertura y uso de suelo del 2017.

III.2. Marco metodológico del modelo hidrológico TETIS

El modelo hidrológico TETIS es una herramienta distribuida espacialmente que permite simular de forma integral los principales procesos del ciclo hidrológico, como la escorrentía directa, el interflujo y el flujo base. Su diseño flexible permite su aplicación tanto a escala diaria como horaria, lo que lo hace adecuado para estudios detallados en cuencas con variabilidad espacial significativa. Una de sus principales fortalezas es la posibilidad de calibración automática, lo cual mejora la eficiencia del proceso de ajuste de parámetros. Para implementar el modelo, se requiere una primera estimación de parámetros a nivel de celda, utilizando información espacial disponible como modelo digital del terreno, usos del suelo y características edáficas del suelo.

La calibración del modelo TETIS se realiza ajustando factores correctores asociados a los distintos procesos hidrológicos simulados (como infiltración, percolación, almacenamiento, evapotranspiración y propagación en cauces), así como el coeficiente que regula el incremento de la precipitación con la altitud. Esta calibración se lleva a cabo de manera iterativa entre escalas diarias y horarias, considerando condiciones iniciales ajustadas manualmente y utilizando periodos de calentamiento que permiten estabilizar el estado hídrico del sistema. Los datos observados, como las precipitaciones y los caudales diarios, se utilizan como base para ajustar el modelo, mientras que en escalas horarias se recurre a series reconstruidas debido a la limitada disponibilidad de datos. El rendimiento del modelo se evalúa mediante indicadores estadísticos como el índice de eficiencia de Nash-Sutcliffe y el balance hídrico, alcanzando valores satisfactorios en la mayoría de los casos. Una vez calibrado, el modelo permite simular de forma continua largos periodos hidrológicos, identificar eventos de crecida, y analizar la respuesta hidrológica de la cuenca bajo distintas condiciones. A pesar de que en algunos casos se ha detectado una tendencia a sobreestimar caudales bajos, el modelo proporciona una herramienta robusta y flexible para la simulación hidrológica, especialmente útil para la gestión de recursos hídricos y la evaluación de eventos extremos como inundaciones (Frances et al., 2008; Gomis-Cebolla et al., 2022; Hurtado-Pidal et al., 2022).

La Figura 2 muestra el marco metodológico para la implementación del modelo hidrológico TETIS, con el cual se desarrollaron los resultados de esta tesis. EL modelo requiere de aproximadamente once mapas para su correcto funcionamiento. El modelo digital del terreno (MDT), se extrajo de ALOS-1 PALSAR imagen con una resolución espacial de 30 metros (<http://vertex.daac.asf.alaska.edu>, accessed January 23, 2023). A partir de este mapa se derivan los mapas de pendiente, velocidad de ladera, dirección y acumulación del flujo, los cuales tributan también al funcionamiento del modelo. La información sobre los suelos (textura, profundidad del suelo, contenido de materia orgánica y permeabilidad) fue extraída de los Estudios Agrológicos de la VIII Región, basados en datos del Centro de Información de Recursos Naturales (CIREN). Los mapas de la capacidad de infiltración (KS) y capacidad de percolación (KP) fueron obtenidos a partir de Tyagi et al. (2022). La capacidad de pérdida del acuífero profundo (KPs) se determinó en función de las características litológicas de las formaciones geológicas de la cuenca. Para la conductividad hidráulica horizontal saturado (Ksa) y la velocidad de flujo del acuífero profundo (Kps), se aplicaron las siguientes suposiciones: $Ksa = Kp$ y $Kps = 0.1 \times Kp$ (Gomis-Cebolla et al., 2022). El almacenamiento estático en la capa superior del suelo (HU) se obtuvo mediante la suma del almacenamiento superficial y el contenido de agua disponible, este último calculado multiplicando la profundidad alcanzada por las raíces por el contenido de agua disponible del suelo. El almacenamiento superficial se calculó a partir de mapas de cobertura del suelo y pendientes, siguiendo el método descrito por (Francés et al., 2007). El contenido de agua disponible se estimó como la diferencia entre la capacidad de campo y el punto de marchitez. Esta información se generó mediante código de Python. Los parámetros en el modelo TETIS que marcan la diferencia entre tipos de superficie de bosque (nativo-forestal) son cuatro: La profundidad de raíces, el factor de vegetación mensual (λ_v), la intercepción y la distribución espacial del HU. Todos estos parámetros se modifican a partir de la distribución espacial de los cambios de cobertura de uso de suelo como se señala mediante corchete rojo del gráfico. Los parámetros fueron ajustados utilizando datos de (Allen et al., 1998; Balocchi et al., 2020; Huber et al., 2010; C. Liu et al., 2017). Todos los mapas fueron trabajados a resolución espacial de 90m. Para el correcto funcionamiento del modelo, solo los procesos de calibración y validación se desarrollaron a resolución de 200 metros. Por otra parte, los datos hidrometeorológicos, tanto los observados como históricos (precipitación, temperatura, Eto,

caudal) fueron determinados a partir del Centro del Clima y la Resiliencia (CR2). Los cambios de cobertura de uso de suelo actuales (1986, 2001, 2011, 2017) fueron obtenidos a partir de la clasificación de (Heilmayr et al., 2016). Antes de iniciar el proceso de calibración y validación, se realizó un análisis de sensibilidad enfocado en el caudal a la salida de ambas cuencas. Para ello, se evaluaron los nueve factores correctores que ofrece el modelo TETIS, con el objetivo de identificar cuáles de ellos presentan mayor sensibilidad ante modificaciones y, por ende, mayor influencia en la simulación del caudal. La evapotranspiración (FC2) y la velocidad en la red fluvial (FC9), fueron los dos parámetros que más sensibilidad mostraron ante cambios mínimos. Por lo que se prestó especial atención a estos durante el proceso de calibración. Finalmente, este proceso se optimizó utilizando el algoritmo automático de optimización Shuffled Complex Evolution - University of Arizona (SCE-UA), el cual está incorporado en el modelo TETIS. La página de descarga del modelo TETIS se encuentra en el siguiente link: https://github.com/GIMHAUPV/Tetis_V9.1interface

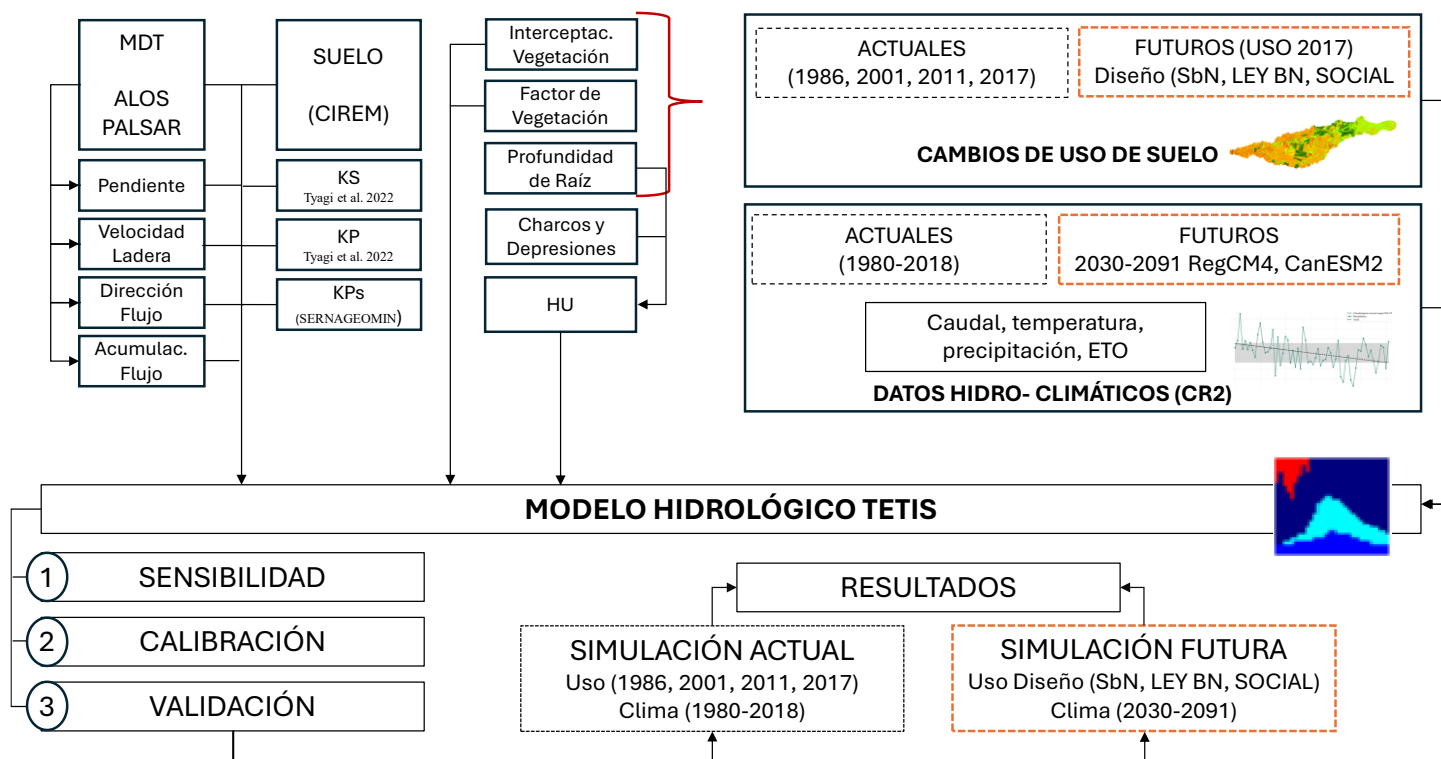


Figura 2. Diagrama de flujo del marco metodológico mediante el modelo TETIS.

III.3. Cambios de cobertura y uso del suelo (LUCC)

La distribución espacio-temporal de los cuatro usos de suelo evidencia una notable pérdida de superficie de bosque nativo en ambas cuencas a lo largo del tiempo. Esta tendencia es especialmente pronunciada en la cuenca del río Quino, donde la superficie de bosque nativo se concentra principalmente en las zonas altas. Los suelos agrícolas, que actualmente ocupan más de la mitad del territorio, no presentan variaciones significativas en su extensión a lo largo de los cuatro años analizados. En contraste, las plantaciones forestales comienzan a ser visibles a partir de inicios de los años 2000, con un crecimiento sostenido en superficie, particularmente en las zonas medias-altas de la cuenca. Este patrón sugiere un avance de las plantaciones sobre áreas anteriormente ocupadas por bosques nativos, matorrales y suelos agrícolas (Figura. 3–4).

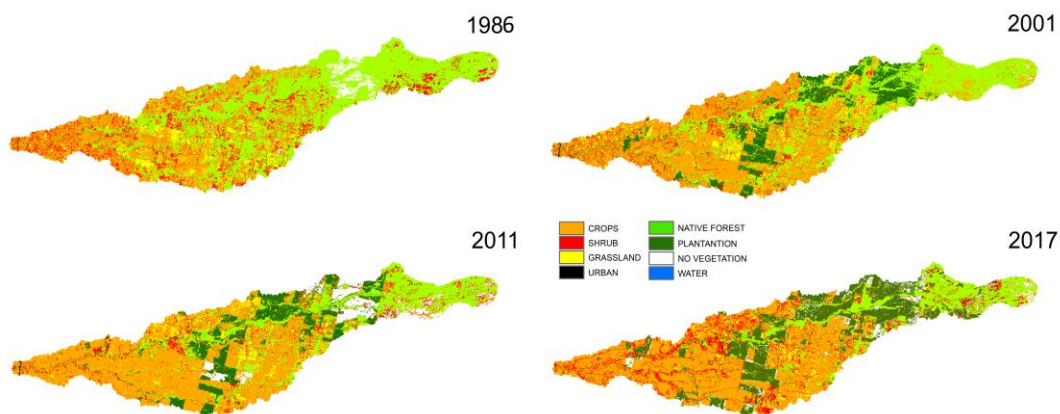


Figura 3. Distribución espacio temporal de LUCC. Cuenca Quino.

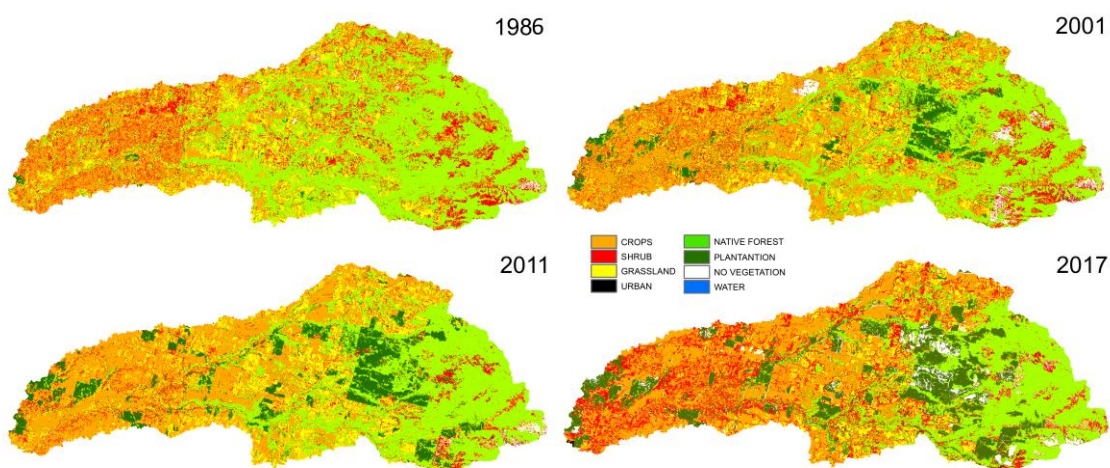


Figura 4. Distribución espacio temporal de LUCC. Cuenca Muco.

Se desarrollaron cuatro escenarios futuros de uso del suelo basados en la clasificación de cobertura de 2017 para las cuencas Quino y Muco, con el objetivo de evaluar los beneficios potenciales sobre el ciclo del agua derivados de la restauración forestal, apoyados en una amplia revisión bibliográfica.

El escenario BN60M se centra en la rehabilitación de zonas ribereñas mediante Soluciones Basadas en la Naturaleza (NBS), cumpliendo con las regulaciones ambientales chilenas respecto al ancho de las franjas ribereñas (200 metros). Los criterios principales para este escenario fueron la restauración, preservación y reforestación de bosque nativo, bajo criterios de soluciones basados en la naturaleza que se pueden consultar como (IDs: 1, 2, 4). El ancho de la franja ribereña se definió siguiendo los lineamientos de protección del bosque nativo en Chile (200 metros en zonas con pendiente abrupta) (IDs: 3, 10, 11), así como dos estudios que evidencian como la franja de 60 metros favorece los servicios ecosistémicos relacionados con el agua (IDs: 8, 9). En conjunto, este escenario se basa en recomendaciones científicas y normativas sobre la preservación, restauración y reforestación de bosque nativo a través de Soluciones Basadas en la Naturaleza.

Los escenarios BN50 y FR50 promueven la restauración a gran escala en las zonas medias y altas de las cuencas bosque nativo y plantaciones forestales. Impulsados por los beneficios hidrológicos esperados, la preservación del patrimonio cultural indígena y las percepciones sociales regionales, como la idea de que “cuando las empresas forestales se van, el agua vuelve”. En ambos escenarios se decidió mantener los suelos agrícolas, ya que, según criterios sociales y de gobernanza, es importante conservar esta actividad (IDs: 4, 12, 13). Sin embargo, en ambos casos se buscó homogenizar el paisaje, siguiendo los criterios de Hernández et al. (2017), quienes indican que la agregación del paisaje ya sea de bosques nativos o plantaciones forestales, tiene distintos impactos en el ciclo del agua. Esto permitió minimizar la incertidumbre respecto a los efectos hidrológicos (Capítulo IV de la tesis). La dimensión de la restauración, superior al 50%, estuvo basada en los lineamientos para restauración a gran escala del método ROAM (ID7), utilizado como ejemplo explícito para una intervención amplia en la zona media-alta de la cuenca.

El escenario BN80 propone una restauración ecológica casi total de la cuenca, excluyendo únicamente las áreas urbanas, los cuerpos de agua y los pastizales. Este escenario actúa como referencia para evaluar el impacto hidrológico de una reconstrucción extensa del bosque nativo. Su formulación se basó en los criterios de restauración a gran escala del enfoque ROAM, en los beneficios reconocidos de los bosques nativos para la disponibilidad de agua, así como en consideraciones sociales y culturales (IDs: 4, 5, 7, 13). El objetivo fue explorar qué tan beneficiosa puede ser una restauración ecológica completa para garantizar el recurso hídrico en un contexto de cambio climático, en comparación con escenarios en los que se mantienen ciertas actividades socioeconómicas dentro de la cuenca. En términos generales, los pastizales se conservaron en todos los escenarios debido a su aporte positivo al balance hídrico, según las Soluciones Basadas en la Naturaleza (ID6).

Para más detalles sobre la construcción de los escenarios, consultar el Capítulo V de esta investigación. En la *sección 2.2. Modeling land-used scenario*, se encuentra una descripción de los criterios de modificación del paisaje, así como la tabla 1 de esa sección, donde se identifica la bibliografía consultada y el porqué de su selección. La superficie que ocupan cada uno de los componentes de los usos de suelo en cada escenario en km², se aprecia en la tabla 1 de este capítulo. La superficie de bosque nativo se fue incrementado ocupando mayormente las zonas de matorral y plantaciones forestales. La Figura 5 muestra la representación espacial del bosque nativo en los distintos escenarios de restauración desarrollados en el Capítulo II de esta tesis. El escenario Land Use 2017 corresponde al uso de suelo del año 2017, donde se observa que para ambas cuencas la superficie de bosque nativo es baja, y se concentra hacia las zonas media-baja, y de rivera de forma aislada. El escenario *BN60M* representa una restauración centrada principalmente en las zonas ribereñas. *BN50* y *FR50* comparten la misma superficie total de restauración, por lo que se presentan en un solo mapa; sin embargo, se diferencian en el tipo de cobertura: *BN50* contempla restauración con bosque nativo, mientras que *FR50* se basa en plantaciones forestales. Finalmente, el escenario *BN80* representa el mayor esfuerzo de restauración, con más del 80% de la superficie cubierta por bosque nativo.

Tabla 1. Cambio de cobertura y uso de suelo por escenario (km²).

LUC	Nativo	Forestal	Agrícola	Matorral	Pasto	Agua	No	Urbano
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	Vegetación							
2017	240.0	152.1	254.1	160.1	71.0	0.4	35.2	3.2
Bn60	312.1	133.5	234.7	134.1	66.7	0.4	31.4	3.2
BN50	586.1	0.0	255.4	0.0	71.0	0.4	0.0	3.2
BN80	841.4	0.0	0.0	0.0	71.0	0.4	0.0	3.2
FR50	0.0	586.1	255.4	0.0	71.0	0.4	0.0	3.2

*2017: Uso de suelo actual.

Bn60: Restauración de zona de ribera 60m.

BN50: Restauración de más del 50% de la cuenca con bosque nativo.

FR50: Restauración de más del 50% de la cuenca con plantaciones forestales.

BN80: Restauración de más del 80% de la cuenca con bosque nativo.

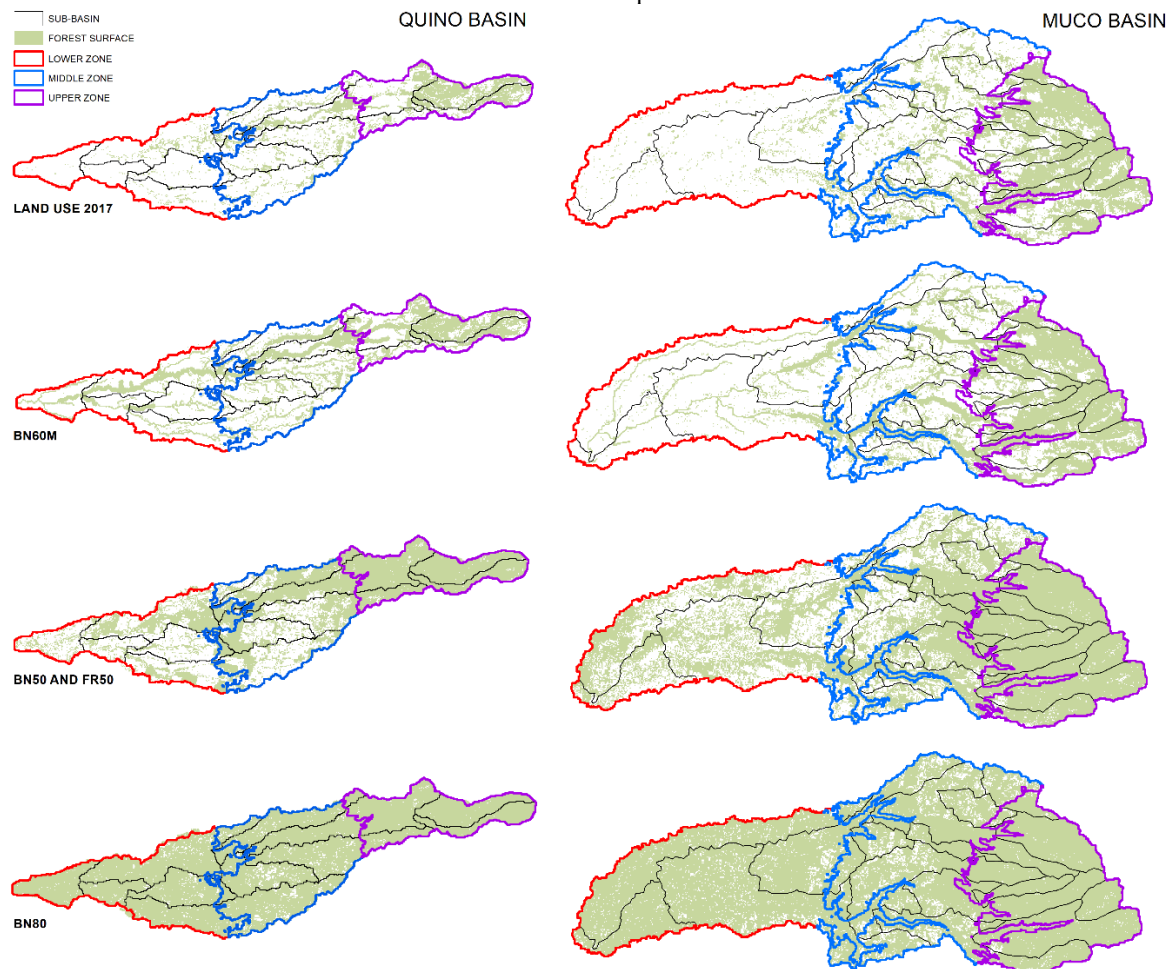


Figura 5. Superficie de bosque nativo presente en las cuencas Quino y Muco.

2017: Uso de suelo actual. Bn60: Restauración de zona de ribera 60m. Bn50: Restauración de más del 50% de la cuenca con bosque nativo. FR50: Restauración de más del 50% de la cuenca con plantaciones forestales.

BN80: Restauración de más del 80% de la cuenca con bosque nativo.

III.4. Métricas del Paisaje

Las métricas del paisaje se calcularon utilizando el software FRAGSTATS v4.2.1, basándose en los cuatro mapas de cobertura de suelo (1986, 2001, 2011, 2017). Las métricas del paisaje se categorizaron en tres niveles: parche, clase y paisaje. Las escalas de parche y clase se analizaron a partir de cinco usos de suelo: Bosque nativo, plantaciones forestales, (jóvenes y adultas), agrícola, matorral y pastizales. En contraste, el nivel de paisaje fue evaluado como una unidad integrada. La Tabla 2 presenta las métricas seleccionadas para el estudio. Para una descripción más detallada, se puede consultar la sección 2.2 del Capítulo I o la documentación disponible en <https://fragstats.org/>.

Tabla 2. Descripción de las métricas del paisaje utilizadas en la investigación.

CATEGORIA	NOMBRE	ESCALA	ABREVIATURA	UNIDAD	DESCRIPCIÓN
Agregación	Índice de proximidad	Parche	PROX	-	Suma del área del parche (m ²) dividida por el cuadrado de la distancia de borde a borde más cercana (m ²) entre el parche y el parche focal de todos los parches del tipo de parche correspondiente cuyos bordes están dentro de una distancia especificada (m) del parche focal.
	Distancia euclidiana al vecino más cercano	Parche	ENN	m	La distancia (m) al parche vecino más cercano del mismo tipo, según la distancia de borde a borde más corta.
	Número de Parche	Parche	NP	-	Número de parches del tipo de parche correspondiente.
	Densidad del Parche	Paisaje	PD	Número por 100 ha	Número de parches de la clase correspondiente por unidad de área. La PD aumenta cuando el paisaje es más complejo (contiene más parches).
	Índice de división del paisaje	Paisaje	DIV	-	Es igual a 1 menos la suma del área del parche (m ²) dividida por el área total del paisaje (m ²), cantidad al cuadrado, sumada en todos los parches del tipo de parche correspondiente.
Contraste	Índice de contraste de bordes	Parche	ECON	%	Suma de las longitudes de los segmentos del perímetro del parche (m) multiplicadas por sus pesos de contraste correspondientes, divididas por el perímetro total del parche (m), multiplicado por 100 (para convertir a un porcentaje).
	Densidad de borde ponderada por contraste	Clase	CWED	m/h	Suma de las longitudes (m) de cada segmento de borde que involucra el tipo de parche correspondiente multiplicada por el peso de contraste correspondiente, dividida por el área total del paisaje (m ²), multiplicada por 10 000 (para convertir a hectáreas).
Forma	Índice de Dimensión Fractal	Clase	FRAC	-	Equivale a 2 veces el logaritmo del perímetro del parche (m) dividido por el logaritmo del área del parche (m ²); el perímetro se ajusta para corregir el sesgo ráster en el perímetro.
	Índice de Contigüidad	Clase	CONT	-	Es igual al valor de contigüidad promedio de las celdas en un parche (es decir, la suma de los valores de las celdas dividida por el número total de píxeles en el parche) menos 1, dividido por la suma de los valores de la plantilla.
Diversidad	Índice de Diversidad de Shannon	Paisaje	SHDI	-	Es igual a menos la suma, en todos los tipos de parches, de la abundancia proporcional de cada tipo de parche multiplicada por esa proporción.

III.5. Análisis estadístico

En el capítulo cuatro (primer artículo), se les da cumplimiento a los objetivos uno y dos de esta investigación: Se analizaron las relaciones entre procesos hidrológicos, caudales y métricas del paisaje en 20 subcuencas mediante correlaciones espaciales y temporales. Se aplicó el coeficiente de correlación de Pearson para evaluar la relación entre las métricas del paisaje (variables independientes) y los procesos hidrológicos y caudales (variables dependientes), considerando valores significativos con $r \leq -0.36$ o $r \geq 0.36$. Se eligió un umbral moderado para identificar patrones y tendencias generales entre la cobertura, métricas del paisaje y el comportamiento hidrológico. Este método permitió detectar señales consistentes, aunque no muy fuertes, facilitando reconocer métricas favorables para los procesos hidrológicos. Este tipo de umbrales se usa comúnmente en análisis exploratorios de sistemas complejos como se aprecia en Epting et al. (2017). Además, se aplicó un análisis de mínimos cuadrados parciales (PLSR) para evaluar la relevancia predictiva de cada métrica. Se utilizó el índice VIP (Variable Importance in the Projection), considerando valores > 1 como relevantes. También se evaluaron los pesos (w) para entender la dirección e intensidad de cada relación. Todos los análisis se realizaron con el software XLSTAT (versión 2023.2.1414). En el capítulo cinco (segundo artículo), se le da cumplimiento al objetivo tres de esta investigación: Se aplicaron diversos métodos estadísticos y análisis cuantitativos para evaluar los efectos del cambio climático y los cambios en el uso del suelo sobre componentes clave del ciclo hidrológico. La precipitación futura fue analizada mediante el Índice de Precipitación Estandarizado (SPI), lo que permitió identificar variaciones estacionales y determinar si las reducciones proyectadas en las precipitaciones se deben a cambios en la frecuencia o en la intensidad de los eventos. Las temperaturas extremas fueron evaluadas a partir de anomalías estandarizadas, complementadas con el análisis de la amplitud térmica para evaluar el efecto en la evapotranspiración. Por otra parte, los cambios en la evapotranspiración real se estimaron a partir de mapas diarios generados por el modelo hidrológico distribuido TETIS, los cuales fueron posteriormente agregados a escala anual para facilitar su análisis comparativo. En cuanto al comportamiento de los caudales, se emplearon tres enfoques a nivel de subcuenca: (i) el análisis del cambio porcentual, (ii) las curvas de duración del caudal, y (iii) un índice de desempeño hidrológico forestal (HPFI, por sus siglas en inglés), que integra superficie forestada, superficie de cuenca y los caudales simulados. Finalmente, se aplicó un balance

hídrico simplificado ($P - E - Q - \Delta S = 0$) para dos trienios representativos (2044–2046 y 2070–2072), seleccionados según condiciones climáticas proyectadas como normales, húmedas y secas. Este enfoque permitió evaluar las dinámicas de entrada, salida y almacenamiento del agua bajo distintos escenarios de cambio climático y uso del suelo.

CAPÍTULO IV. THE RESPONSE OF THE WATER CYCLE TO LANDSCAPE CONFIGURATION AND COMPOSITION IN TWO CHILEAN BASINS

Resumen

El cambio en el uso y cobertura del suelo (LUCC, por sus siglas en inglés) y los patrones del paisaje tienen una influencia significativa en el ciclo hidrológico. No obstante, aún existe un conocimiento limitado sobre cómo responden los procesos hidrológicos y el comportamiento del caudal a las variaciones en la configuración y composición del paisaje dentro de las cuencas hidrográficas. En este estudio se analizó la relación entre métricas del paisaje y variables hidrológicas en dos cuencas ubicadas en Chile durante un período de cuatro décadas. Para ello, se utilizaron métricas relacionadas con la agregación, la forma y la diversidad del paisaje, obtenidas a través del software Fragstats, mientras que los componentes hidrológicos fueron simulados utilizando el modelo hidrológico distribuido TETIS. A fin de determinar la influencia de los patrones del paisaje sobre los procesos hidrológicos y el comportamiento del caudal, se aplicaron análisis de correlación de Pearson (PCC) y de regresión por mínimos cuadrados parciales (PLSR).

Los resultados indican que las correlaciones negativas más significativas se presentan durante la estación húmeda, particularmente entre las métricas de agregación y forma asociadas a suelos de cultivo, y los componentes hidrológicos como la evapotranspiración, la infiltración y el régimen de caudal base. Esto sugiere que cambios en la configuración espacial de estas tierras agrícolas pueden reducir la eficiencia de los procesos hidrológicos clave. Además, el análisis PLSR reveló que la segunda componente, relacionada con métricas del paisaje de plantaciones jóvenes, explica el mayor porcentaje de variación en los componentes hidrológicos. Este hallazgo subraya la relevancia de los cambios en la cobertura forestal y la edad de las plantaciones en la dinámica del ciclo del agua.

En conjunto, estos resultados aportan nuevos conocimientos sobre cómo la configuración y composición del paisaje influyen en el ciclo hidrológico. Esta información puede ser de gran utilidad para la planificación del uso del suelo y la gestión sostenible de los recursos hídricos en cuencas hidrográficas con dinámicas de uso de suelo cambiantes, como ocurre en muchas regiones de Chile.



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Keywords: TETIS, Landscape pattern, Hydrological process, Streamflow Basins, Chile

Abstract

Land use/cover change (LUCC) and landscape patterns have an important influence on the hydrological cycle. However, it is still unknown how hydrological processes and streamflow respond to changes in landscape configuration and composition in hydrological basins. The relationship between landscape metrics and hydrological variables in two Chilean basins was analyzed for the last 4 decades. Aggregation, shape and diversity metrics were obtained using Fragstats software, and hydrological components were simulated by the TETIS hydrological model. Pearson correlation coefficients (PCC) and partial least squares (PLSR) analysis were used to determine how landscape patterns influence hydrological processes and streamflow behavior. The most significant negative correlations occur in the wet season between

aggregation and shape metrics on crop soils and evapotranspiration, infiltration, and baseflow regime behavior. The PLSR analysis shows that the second component-related landscape metrics of young plantations explain the highest percentage of variation in hydrological components. The results of this research improve our understanding of the effects of landscape configuration and composition on the hydrological cycle and can be used for land planning and water resource management within the basins.

1. Introduction

Human-nature interactions are directly reflected in land use and land cover change (LUCC), which systematically alters natural landscapes (Foley et al., 2005; Steffen et al., 2015; Yang et al., 2024). Anthropogenic interventions significantly reduce basin regulatory capacity and water yield, regardless of the hydrological characteristics of the original biome (Ochoa-Tocachi et al., 2016). These changes in landscape composition (proportion and size of each land use/cover) and configuration (distribution and spatial characteristics of landscape patches) reduce the capacity of ecosystems to provide ecosystem services (Yohannes et al., 2021). In particular, inadequate LUCC management affects surface runoff (Berihun et al., 2019; T. Huang et al., 2019), groundwater dynamics, percolation and lateral flow, exacerbating water scarcity in basins (Martínez-Retureta et al., 2020; Renée Brooks et al., 2010). There is also evidence of a relationship between the expansion of forest plantations and a decrease in baseflow, low-flow regimes and basin regulatory capacity (Albaugh et al., 2013; Alvarez et al., 2013; Buytaert et al., 2007; Jullian et al., 2018; Martínez-Retureta et al., 2020a). However, conflicting results suggest that changes in vegetation cover do not significantly affect the behavior of hydrological cycle components. For example, Hawtree et al. (2015) and Wine & Zou, (2012) argue that this relationship is not evident, while others claim that forest restoration does not improve surface water yield (Kurzweil et al., 2021). For instance, Pizarro et al. (2005) hypothesized that the expansion of *Pinus radiata* plantations would lead to water losses in the Purapel River basin in Chile; however, their study did not find significant hydrogeological changes. On the other hand, Brooks et al. (2010) suggest that forest plantations have a stabilizing role in the balance between precipitation, surface runoff, and aquifer recharge.

In recent decades, the study of the influence of landscape spatial patterns on the hydrological response of basins has gained considerable attention in the environmental sciences. Landscape patterns provide a comprehensive framework for analyzing the distribution and interconnection of water flow across different land surfaces and cover types. A fundamental tenet of landscape ecology is that spatial patterns and ecological processes and functions are coupled. Hydrology is one of the primary drivers of ecological processes and vegetation, in particular, can strongly influence hydrology and create feedback (via flow occlusion, evaporation gradients, changes in bed friction, and changes in water storage) that can, in turn, shape landscape structure and function (Yuan et al., 2015). Several studies have demonstrated the relationship between landscape metrics and changes in erosion and sedimentation regimes within hydrographic basins. These metrics include the Shannon diversity index, aggregation index, largest patch index, contagion index, and patch cohesion index (Da Silva et al., 2015; Z. H. Shi et al., 2013). Additionally, research has emphasized that well-connected landscapes can effectively mitigate soil erosion (Jiang et al., 2020). Other metrics related to area, shape, interception, and connectivity have been shown to influence surface runoff, baseflow, and percolation dynamics (Boongaling et al., 2018; Frey et al., 2021).

Hydrological models have been extensively used to explore interactions between landscape patterns and the components of the hydrological cycle (Haas et al., 2022). These relationships have predominantly been analyzed using semi-distributed or one-dimensional hydrological models (Aygün et al., 2022; Chen et al., 2024; Haas et al., 2022; Li & Zhou, 2015; L. Lyu et al., 2023, Y. Lyu 2023; Ma et al., 2023; Mangi et al., 2022; Zhou & Li, 2015; Zong et al., 2020). For instance, the SWAT model divides watersheds into sub-watersheds and calculates runoff and sediment generation based on combinations of land use, soil type, and slope. However, SWAT does not account for the influence of landscape patterns on streamflow convergence or sediment transport processes. Consequently, SWAT-based hydrological simulations may overlook critical effects of landscape patterns on hydrological dynamics (Wei et al., 2023). In contrast, the TETIS model is a spatially distributed hydrological model with physically based parameters that simulate the main components for the terrestrial phase of the hydrological cycle using a regular grid (Francés et al., 2007a). Its has been implemented

in mountain regions characterized by humid climates at daily (Peña et al., 2016), and sub-daily time scales (Hurtado-Pidal et al., 2022, 2025), as well as in Mediterranean environments and mid-to-high altitude mountain regions, akin to the study area under consideration (Bussi et al., 2014; Casado-Rodríguez & Del Jesus, 2022; Francés et al., 2007a; Gomis-Cebolla et al., 2022a). By incorporating pixel-level detail into their analysis, distributed models have shown enhanced efficiency in capturing landscape spatial patterns. This capacity enables them to more accurately reflect the behavior of hydrological processes, as they can account for spatial and temporal variations in terrain characteristics such as topography, vegetation, and land use.

This research focuses on two sub-basins of the Imperial River, situated in the south-central region of Chile. This territory has undergone significant LUCC changes, particularly due to unsustainable practices (Aguayo et al., 2009a; Echeverría et al., 2012a; Heilmayr et al., 2016a; Rodríguez-Echeverry et al., 2018a). Furthermore, the region has been experiencing increasing water stress for over a decade, a situation that is further exacerbated by future climate scenarios projecting up to a 40% reduction in precipitation (Araya-Osses et al., 2020; Garreaud et al., 2020). Prior studies have predominantly been centered on the impact of landscape pattern on water availability and sedimentation regimes (Chisola et al., 2020; D. N. Moriasi et al., 2007; Hu et al., 2021; Li et al., 2021; J. Liu et al., 2020; Lyu et al., 2023a; Mangi et al., 2022; Yohannes et al., 2021; G. Zhang et al., 2013). However, this study aims to establish the relationship between landscape patterns, a broader range of hydrological processes, and streamflow, with particular attention to the seasonality of the Mediterranean climate. This focus is crucial because annual datasets frequently obscure the variability of water cycle components, which are highly sensitive to seasonal patterns (Chisola et al., 2020; Haas et al., 2022; Y. Han et al., 2021; J. Liu et al., 2020; H. Ma et al., 2023). The findings of this study are expected to advance the understanding of the relationship between landscape patterns and a broader range of hydrological processes in Mediterranean climate zones, specifically within the in-tramontane valley situated between the Andes and the Chilean Coastal Mountain Range. This enhanced comprehension is imperative for the development of integrated watershed management strategies that prioritize the conservation of water resources, soil, and forest ecosystems. The objectives of the present study were as follows: (1) to explore how landscape patterns affect the main hydrological processes and (2) to determine

which landscape patterns have higher impact on water provision for the Quino and Muco basins located on the south-central region of Chile.

2. Methodology

2.1. Study area.

The Quino and Muco basins are located within the IX Region of Araucanía in southern Chile, situated at geographical coordinates of (38° 00' 00" S, 72° 20' 00" W - 71° 45' 00" W) according to the WGS84 datum. The area of the Quino and Muco basins is 301 and 649 square kilometers, respectively. The elevations of these basins range from 307 to 1714 meters above sea level (MASL) and from 190 to 1453 MASL, respectively. Mediterranean climate predominates, exhibiting a gradual transition towards a temperate rainy climate in the upper area of the Quino basin. The wet season extends from April to September, while the dry period occurs from October to March. The annual rainfall average ranges from 1800 to 1900 millimeters. The average annual temperature is approximately 10.0°C, with the highest average temperatures recorded in the driest months and the lowest in the wettest months (Fig. 1). The Andisol order soil, a silty loam type, predominates in the region. These soils are characterized by their depth, moderate permeability, and adequate drainage. The current land cover composition in both basins is dominated by crops (27%), native forest (26%), shrubland (17%), plantations (17%), grasslands and soils devoid of vegetation (11%), urban areas (0.34%), and water bodies (0.03%), as depicted in Figure 1. The Quino basin exhibits a higher percentage of its territory being intervened (55%), while the Muco basin has (39%).

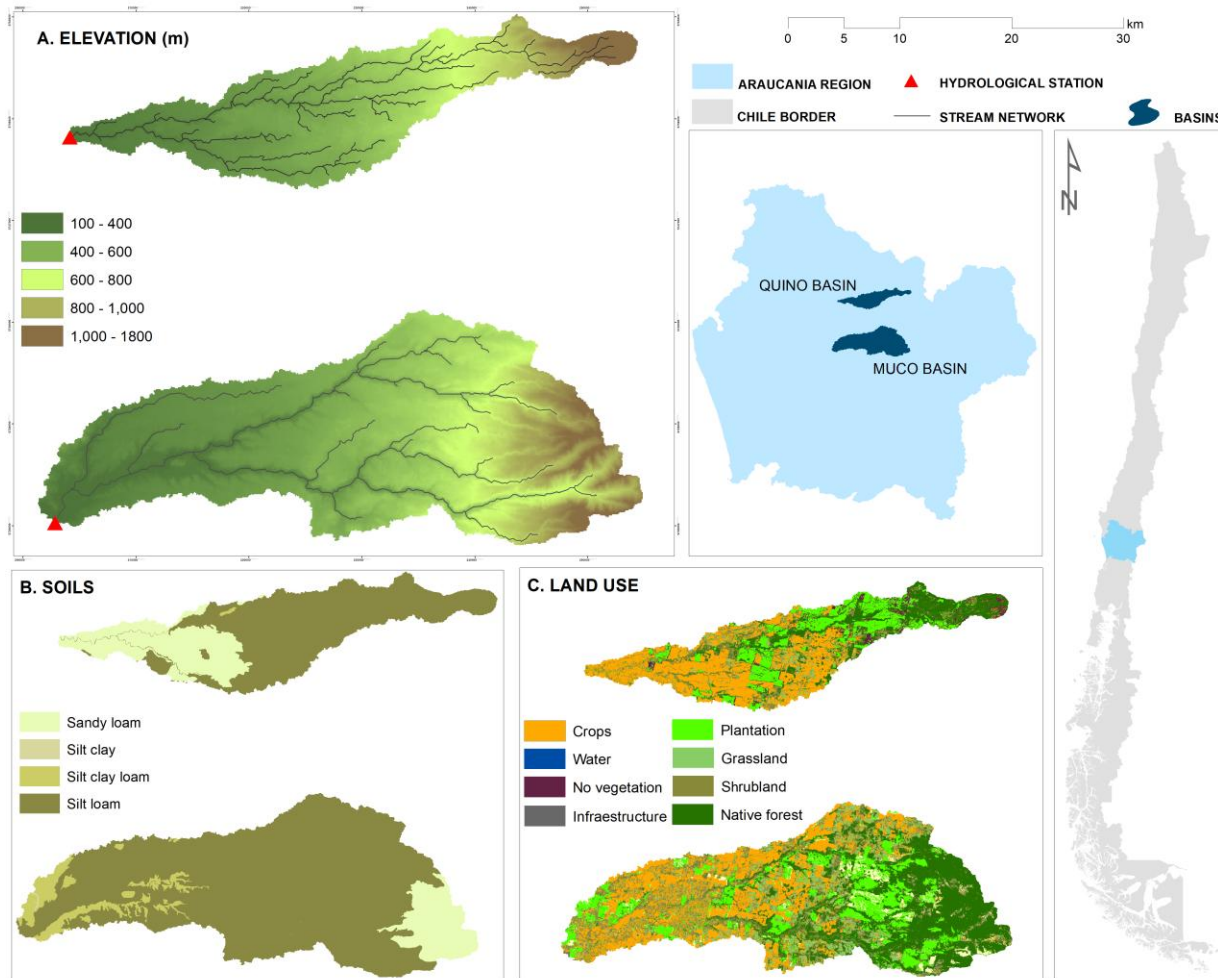


Fig. 1. Location, topography, soil, and 2017 land use of Quino and Muco basins.

2.2. Land uses and landscape metrics.

The Quino and Muco basins have experienced a significant reduction in native forest cover, with a decline of 20-30% observed in the area. The most substantial decline occurred between 1986 and 2011. Forest plantations have increased in both basins over this period, which initially occupied negligible percentages in 1986. By 2017, these plantations had expanded to encompass 20% of the Quino basin and 15% of the Muco basin, representing an area comparable to the current extent of native forests, particularly in the more extensively altered Quino watershed. Agricultural land has consistently covered 20-30% of the territory since 1986, showing an increasing trend, though not as rapidly as forest plantations. Shrubland have expanded, while grasslands have declined, with shrubland currently occupying approximately

10% of the area and exhibiting minimal variation over time (1-4%). Both basins have limited areas covered by urban land and water bodies (Table 1). For a more comprehensive examination of the LUCC spatial distribution of both basins, please refer to the supplementary material (*See Figs. 3-4, from chapter 3.2 on top of the Thesis*).

Table 1.

LUCC distribution for the years 1986, 2001, 2011, and 2017 in the Quino and Muco basin (ha).

LUCC	QUINO				MUCO			
	1986	2001	2011	2017	1986	2001	2011	2017
Native forest	14714	10041	7868	6103	31751	25420	22558	18725
Forest plantation	102	3976	3949	6036	588	4499	7616	9957
Crops	8112	11523	11095	10527	13243	18337	18900	15808
Shrubland	4039	2487	3000	4302	10281	8859	5868	12080
Grassland	2024	1837	2101	1394	8877	7090	9854	6014
Water	3.1	2.1	1.6	17	0	0.8	3	15
No vegetation	934	53	1902	1410	433	966	373	2385
Urban	6.0	14	16	144	0	0.3	0.3	187

For the present study, five of the eight land uses classified within the territory were selected for the purpose of exploring the relationship between hydrological processes and landscape metrics. The selected land uses were as follows: native forests (NF), forest plantations separated as young plantations (YP) and mature plantations (MP), crops (CR), shrubland (SC), and grasslands (GR). The landscape metrics were calculated using the FRAGSTATS v4.2.1 software, based on 4 spatial-temporal land cover maps (1986, 2001, 2011, 2017), classified by Heilmayr et al. (2016), with a resolution of 30 meters (see Fig. S.1-2 in the supplementary material). The landscape pattern matrices were quantified in 20 sub-watersheds at a spatial scale, with a focus on runoff in the main channel and major tributaries, using the flow accumulation map (see Fig. S.3 from the supplementary material). The landscape metrics were categorized at three level matrices: patch, class, and landscape levels. The patch and class scales were further subdivided according to the five selected land uses. In contrast, the landscape level was evaluated as an integrated unit. The aggregation metrics selected have been widely used in previous studies analyzing the relationship between landscape and the hydrological response of basins (Chisola et al., 2020; Wang et al., 2022; Yohannes et al., 2021; Yu et al., 2023). Another set of metrics used in previous studies, such as the proportion index (PLAND), class area (CA), configuration index (CI), largest patch index (LPI), edge

density (ED), total edge density (TE), landscape shape index (LSI), juxtaposition index (JI), splitting (SPLIT), aggregation (AI), and connectivity index (COHESION) (El Jeitany et al., 2024; Y. Han et al., 2021; Lyu et al., 2023a; C. Wu et al., 2024; Yohannes et al., 2021; L. Zhou et al., 2023), were discarded due to the lack of significant results with our data. The second criterion was based on a process of autocorrelation between metrics. The Pearson correlation coefficient (PCC) ≥ 0.6 criterion was used because it is a robust value that has been employed in prior studies (Hughes et al., 2022; Javed et al., 2021; Minh et al., 2024; Rosario et al., 2020; Sakamat et al., 2018; Secci et al., 2021; Vasileiou et al., 2019). Based on this analysis, the sample size was reduced, and data redundancy was minimized. Table 2 presents a comprehensive list of landscape metrics for this study. (See Table 2. from chapter 3.3, on top of the Thesis). For a more in-depth analysis of these metrics, please refer to McGarigal & Marks (1995).

Table 2.
Landscape metrics selected in the study.

CATEGORY	NAME	ABBREVIATION	UNIT
AGGREGATION	Proximity Index	PROX	-
	Euclidean Nearest-Neighbor Distance	ENN	m
	Number of Patches	NP	-
	Patch Density	PD	Number per 100 ha
	Landscape division index	DIV	-
CONTRAST	Edge Contrast Index	ECON	%
	Contrast Weighted Edge Density	CWED	m/h
SHAPE	Fractal Dimension Index	FRAC	-
	Contiguity Index	CONT	-
DIVERSITY	Shannon's Diversity Index	SHDI	-

2.3. Hydro-meteorological records

The hydrometeorological data (i.e., rainfall, temperature, evapotranspiration, and streamflow) were obtained on a daily time frame for the period 1980-2018. This data set was retrieved from a database available at the Climate Research and Resilience Center (<https://www.cr2.cl/>). It includes data of continental Chile for a regular grid of 0.05° latitude by longitude. The CR2MET models are fed with a combination of data, including different variables from the ECMWF ERA5 reanalysis, topographic parameters, and land surface temperature estimates from the Moderate Resolution Imaging Radiometer Satellite Sensor (MODIS). The evapotranspiration and streamflow data were obtained from meteorological and hydrological stations located at the outlet of the basins: Puente Muco (Muco) and Longitudinal (Quino)

(see Figure 1). Seasonal matrices (i.e., annual, wet, and dry) were computed for the following 9 hydrological processes: soil moisture (H1), superficial storage (H2), vegetative cover storage (H6), infiltration (X3), percolation (X4), evapotranspiration (Y1), runoff (Y2), interflow (Y3) baseflow (Y4), and the streamflow (SF), at the spatial scale of 20 sub-watersheds. These variables were derived from the daily spatiotemporal distribution obtained from the TETIS hydrological model (1980–2018). The conversion of daily to seasonal data was developed using ArcGIS 10.3 and MATLAB R2023a.

2.4. Hydrological modeling

TETIS is a spatially distributed conceptual hydrological model with physically based parameters (Francés et al., 2007). A series of parameters are required for the correct functioning of the model, which will be described below. The land use maps were obtained from the classification of Heilmayr et al. (2016) with a resolution of 30 meters. The information of soils (i.e., texture, soil depth, organic matter content, and soil permeability) was extracted from the Agrolological Studies of the VIII Region based on data from the Natural Resources Information Center (SERNAGEOMIN, 2002) (CIREN) for 2002. The map of the lithological information was extracted from the National Catalog of Geological and Mining Information of Chile at a scale of 1:1 000 000 (SERNAGEOMIN, 2002). The digital terrain model (DTM) was extracted from ALOS-1 Palsar images which have a spatial resolution of 30 meters (<http://vertex.daac.asf.alaska.edu/> accessed on January 23, 2023). Parameters such as flow direction and accumulation, slope velocity, and slope were carried out through the MDT. Static storage in the upper soil layer (HU) was achieved through the sum of surface storage and available water content, the latter of which was calculated by multiplying the depth reached by roots by the available water content of the soil. Surface storage was calculated from land cover and slope maps, following the methods outlined in Francés et al. (2007) and Velez et al. (2009). The available water content was calculated as the difference between field capacity and the wilting point. This information was produced by using Soil Water Characteristics (SWC) Version 6.02.74 (Saxton & Rawls, 2006). The root depth was estimated from vegetation land cover maps, as previously described by Francés et al. (2007) and Meléndez D. (2014). The infiltration capacity (KS) and percolation capacity (KP) were obtained from the shallow (0–40 cm) and deep (40–100 cm) soil properties, respectively. The

loss capacity of the deep aquifer (Kps) was determined by the lithological characteristics of the geological formations of the basin. In the case of saturated horizontal hydraulic conductivity (Ksa) and deep aquifer flow velocity (Kps), the following assumptions were considered: $Ksa = Kp$ and $Kps = 0.1Kp$ (Gomis-Cebolla et al., 2022a). The interception and cultivation index values were estimated based on the studies of (Balocchi et al., 2023; Frances & Munera, 2008; Huber et al., 2010; C. Liu et al., 2017), based on the coverage of plants present in the land uses of the region. All maps were developed at resolution of 200 meters and 90 meters, thereby optimizing the calculation capacity of the model and obtaining results with the spatial resolution necessary for the study.

2.5. Calibration and validation of the hydrological model

Model calibration and validation were performed at daily intervals (m^3/s). The observed and simulated discharge data at the outlet of both basins were compared (Fig. 2). The model was calibrated for the period 1986-1988 and validated for the period 1990-1992, using the base land cover of 1986. The calibration/validation data were selected based on the availability of wet, dry, and normal periods. This was done to capture the seasonal dynamics of the study area. In addition, validation was performed with 2017 land use data to evaluate the model under different conditions (see Figure S4 in the Supplementary Material). Several statistical metrics were used to measure the goodness of fit between model outputs and observations. First, the Nash index (Nash & Sutcliffe, 1970) was chosen to determine the relative magnitude of the residual variance ("noise") compared to the variance of the measured data. The RSR ratio, which relates the root mean square error (RMSE) to the standard deviation of the observations, was also used. Finally, the percentage bias (PBIAS) was used to determine the average tendency of the simulated data to be larger or smaller than their observed counterparts (D. N. Moriasi et al., 2015). The fit of the TETIS model was performed by applying correction factors (CFs) to each parameter (water cycle components) to obtain effective parameters (Francés et al., 2007a). A sensitivity analysis with CFs was conducted to identify influential parameters. Then, a manual calibration process was carried out by adjusting the CFs within the initial range of values given by Buendia et al. (2016). Finally, this process was improved by using the automatic optimization algorithm Shuffled Complex Evolution - University of Arizona (SCE-UA), which is included in the TETIS model (Casado-Rodríguez & Del Jesus,

2022). The search ranges for the CFs, along with the final values obtained and applied during the calibration and validation process for the Quino and Muco basins, are presented in Table 3.

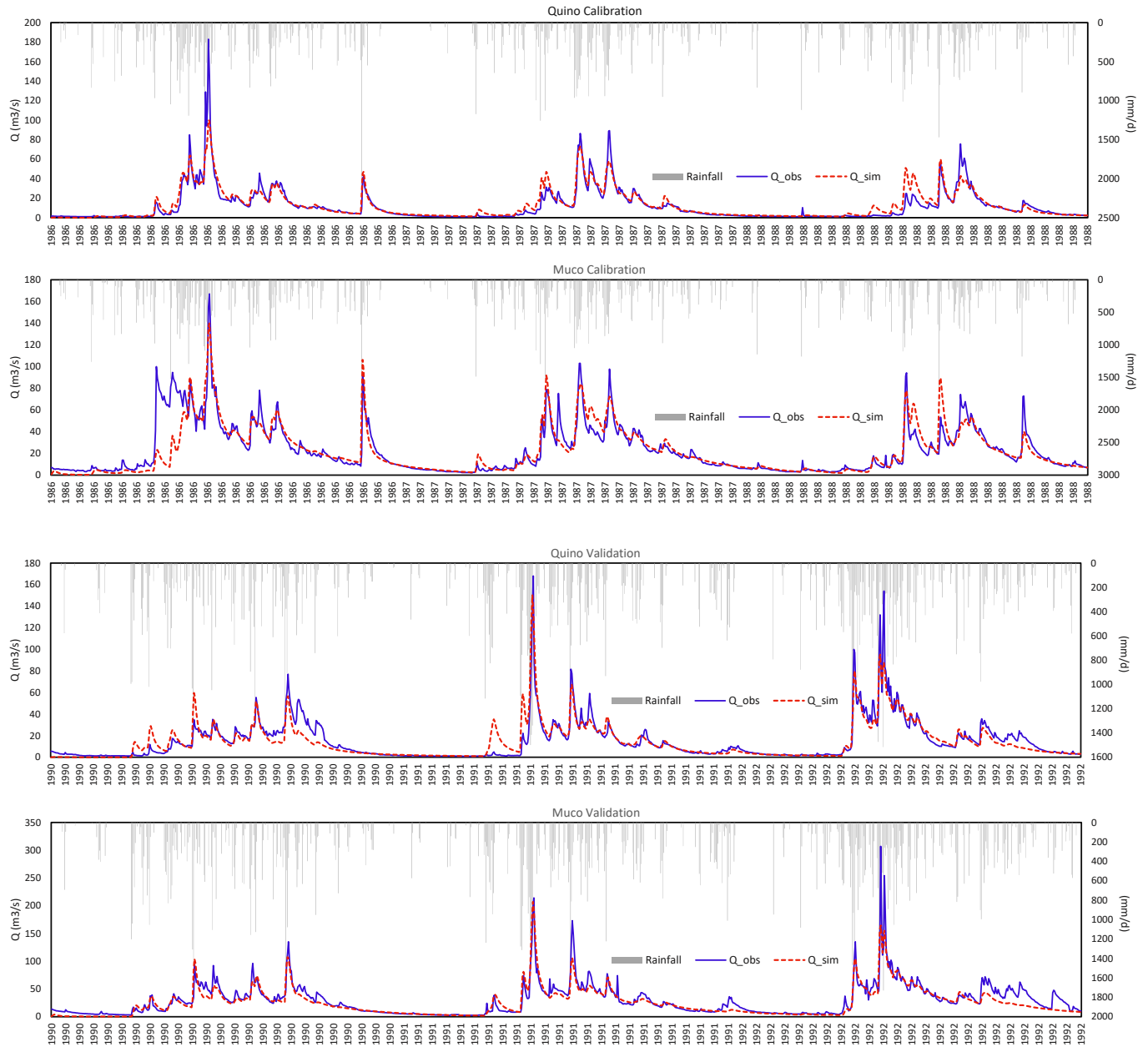


Fig. 2. Calibration (1986-1988) and Validation (1990-1992) of Quino and Muco basins. Land use 1986.

Table 3.

Search range, initial value and final value applied in the calibration and validation of the CFs related to the runoff generating processes (mm).

CORRECTION FACTOR	parameters	MINIMUM	INITIAL	MAXIMUM	FINAL VALUE
FC-1	Soil static storage	0.1	1.0	3.0	2.5-0.6
FC-2	Evapotranspiration	0.0	1.5	3.0	2.5-2.1
FC-3	Infiltration capacity	0.0	0.5	1.0	0.5
FC-4	Overland flow velocity	0.1	2.5	5	0.3
FC-5	Percolation capacity	0.0	0.2	1.0	0.1-0.2
FC-6	Interflow velocity	50	100	300	250
FC-7	Groundwater outflow capacity	0.0	0.5	1.0	0.01-0.07
FC-8	Base flow velocity	50	250	500	480
FC-9	Channel flow velocity	0.0	0.5	1.0	0.1

* Final Value: The first and last values are for Quino and Muco respectively.

2.6. Model Performance

The calibration and validation of the hydrological model shows good results, as seen in Fig. 2. In both basins, the NSE for calibration, and validation were satisfactory ($0.73 \leq NSE \leq 0.86$; Table 4). Moreover, the Quino basin showed the highest values of the index ($NSE \geq 0.83$). In the case of the RSR, the basins showed good performance for calibration and validation ($0.37 \leq RSR \leq 0.51$). In the case of the PBIAS index, the basins also showed good performance ($-7.4 \leq PBIAS \leq 10.2$). The model tends to underestimate the streamflow's in most of the runs; and fundamentally overestimates the first peaks of the rainy period of 1987 and 1988 in the calibration of the Quino basin. However, considering the three evaluation techniques, the calibration and validation results were satisfactory (Table 4). Additionally, to demonstrate the representativeness of the hydrological response in our study area for more recent periods, we present additional validations for Quino (2016-2018) and Muco (2014-2016) basins, using the land use of 2017. The validation performance was satisfactory for the Quino basin ($NSE=0.55$) and very good for Muco, ($NSE=0.80$) (See Fig.S.4 from supplementary material).

Table 4.
Hydrologic Model Performance. Quino and Muco basins.

Metrics	Quino Basin		Muco Basin	
	Calibration (1986-1988)	Validation (1990-1992)	Calibration (1986-1988)	Validation (1990-1992)
NSE	0.86	0.83	0.73	0.83
RSR	0.37	0.40	0.51	0.40
PBIAS	-7.4%	3.8%	4.2%	10.2%

2.7. Statistical analysis.

The spatiotemporal distribution of hydrological processes and streamflow, along with the landscape metrics at a spatial scale of 20 sub-watersheds, were used to create the correlation matrices, hydrological data (i.e., annual, wet, and dry), and landscape pattern (i.e., patch, class, landscape) (see Sections 2.2-2.3 for insight into the seasonal matrices developed). The Pearson correlation coefficient (r) was used, with hydrological processes and streamflow treated as dependent variables and landscape metrics treated as independent variables. This statistic was chosen since it has been used in previous research, achieving positive results (Y. Cao et al., 2023; Li & Zhou, 2015; Martínez-Retureta et al., 2020a; Yohannes et al., 2021; M.-S. Zhang et al., 2021). The calculated values were significant at the 95% confidence interval, with a range of ≤ -0.36 and ≥ 0.36 .

In order to determine the extent of influence on the prediction of hydrological processes and streamflow (as the dependent variable), a linear multivariate model was constructed for the LUCC (agricultural, young forest and native forest), which showed the strongest relationships between landscape metrics and water cycle components. The standardized coefficients obtained by this model allow the identification of the variables that contribute more or less to the explanation of the dependent variable. To ascertain the predictive relevance of each landscape metric on the behavior of hydrological processes and streamflow, a partial least squares analysis (PLSR) was conducted with a 95% confidence interval. The Variable Importance in the Projection (VIP) index was used, with values > 1 considered relevant and values < 0.5 deemed weak (Yohannes et al., 2021). The weight (w) provides insight into the

direction and magnitude of the relationship between landscape metrics and hydrological processes, as well as streamflow, leading to the identification of the most important variables (Stonet & Brooks, 2023). All statistical analyses were conducted using XLSTATS, version 2023.2.1414 (XLSTAT | Excel statistical software).

3. Results

3.1. Spatiotemporal variability of water cycle components and landscape metrics

The landscape patterns observed in both basins are indicative of the land use changes over the past years (see Fig. S.1-2 in the supplementary material). From 1986 to 2017, the landscape of native forests exhibited increased dispersion, fragmentation, and reduced connectivity. Metrics related to the distance between patch edges (PROX and ENN) have increased, while the number of patches has decreased, as have the CONT contiguity and edge density of CWED patches. Conversely, mature and young plantations have increased, resulting in more connected and less dispersed land uses. The patch number and CONT and CWED values have increased. Agricultural land uses showed an increase in patch edge proximity, an increase in segment length, and a decrease in patch number. FRAC, CONT, and CWED metrics showed an increase with minimal variation. Shrublands demonstrated a substantial decrease in PROX and NP, which is considerably more than the increase observed in these metrics for grassland uses. At the landscape level, the number of patches and diversity have increased, primarily for those associated with forest plantations and agricultural soils (Fig. 3-4).

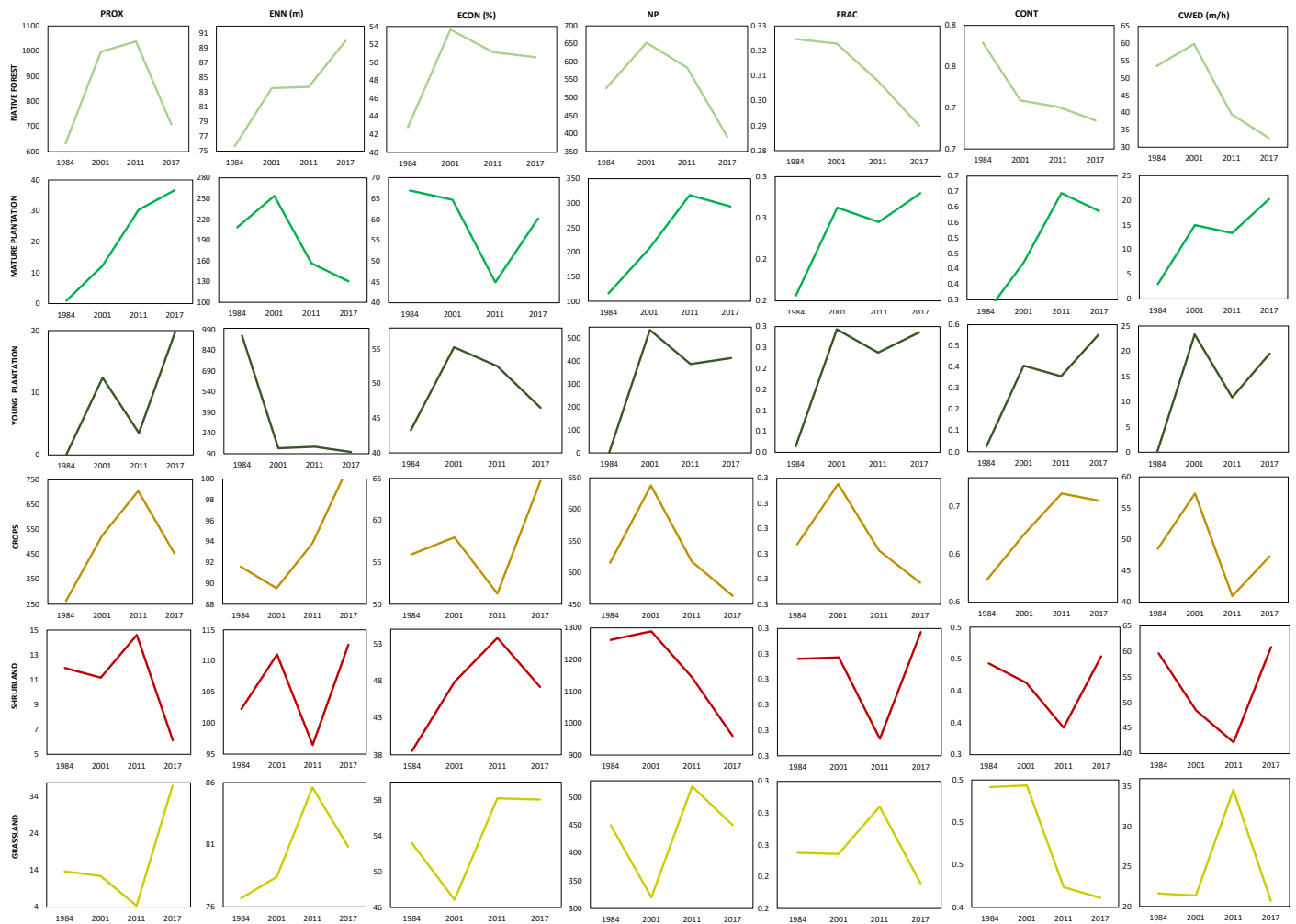


Fig. 3. Patch & Class metrics temporal variation for each LUCC, for both basins. Proximity Index (PROX), Euclidean Nearest-Neighbor Distance (ENN), Edge Contrast Index (ECON), Number of Patches (NP), Fractal Dimension Index (FRAC), Contiguity Index (CONT), Contrast Weighted Edge Density (CWED).

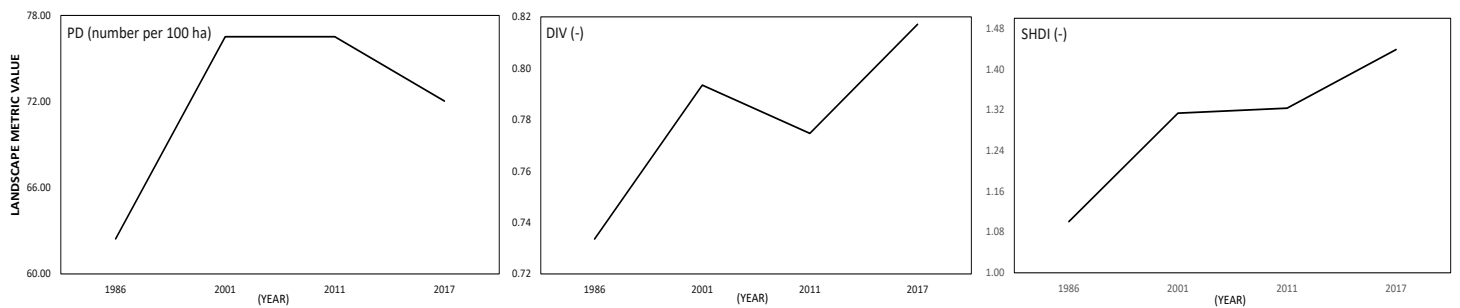


Fig. 4. Landscape metrics temporal variation for both basins. Patch Density (PD), Landscape division index (DIV), Shannon's Diversity Index (SHDI).

Figures 5A and 5B illustrate the spatial distribution of hydrological processes accumulated over the annual period from 1980 to 2018. The highest values for each process are described

as follows. Soil moisture (H1) reached its maximum value (55-68%) in the upper regions of the basins, which corresponded to areas covered by native forests. Surface storage (H2) ranged from 80 to 160 mm in the intermediate basin zones, while vegetative cover storage (H6) ranged from 150 to 200 mm in the forest plantation areas. Infiltration (X3) showed a peak of approximately 300 mm in the upper basin areas, and percolation (X4) exceeded 200 mm in the upper-middle zone, closely linked to the spatial distribution of static soil storage. Evapotranspiration (Y1) ranged from 170 to 350 mm in the upper-middle zone, where both forest plantations and native forests are present. Runoff (Y2) registered maximum values between 1000 and 3000 mm in the highland and riverside areas, while interflow (Y3) ranged from 900 to 2000 mm in the upper-middle zone. The base flow (Y4) ranged from 450 to 550 mm in areas dominated by forest plantations and the steepest slopes.

The analysis of the temporal distribution of hydrological processes and streamflow for both basins, covering the period from 1980 to 2018, is based on the average accumulations for the annual, rainy, and dry seasonal periods, as illustrated in Figure 6. The annual trend line reveals a decline in hydrological processes such as percolation, interflow, base flow, and streamflow. Conversely, processes such as evapotranspiration and vegetative cover storage show a tendency to increase. No discernible trend was observed for surface runoff, infiltration, or soil moisture, as these variables remained relatively constant throughout most seasonal periods, as indicated by the graph. The analysis of the hydrological processes indicates that soil moisture and surface storage exhibit the greatest variability, with significant divergence between values observed during the wet and dry periods. This is followed by base flow, streamflow, and runoff. The smallest fluctuations between mean values of the seasonal periods are observed in evapotranspiration and vegetative cover storage. Infiltration demonstrates the most significant variability within its series, while vegetative cover storage exhibits the most pronounced deviation from mean values during the wet period, starting from 1998 (Fig. 6).

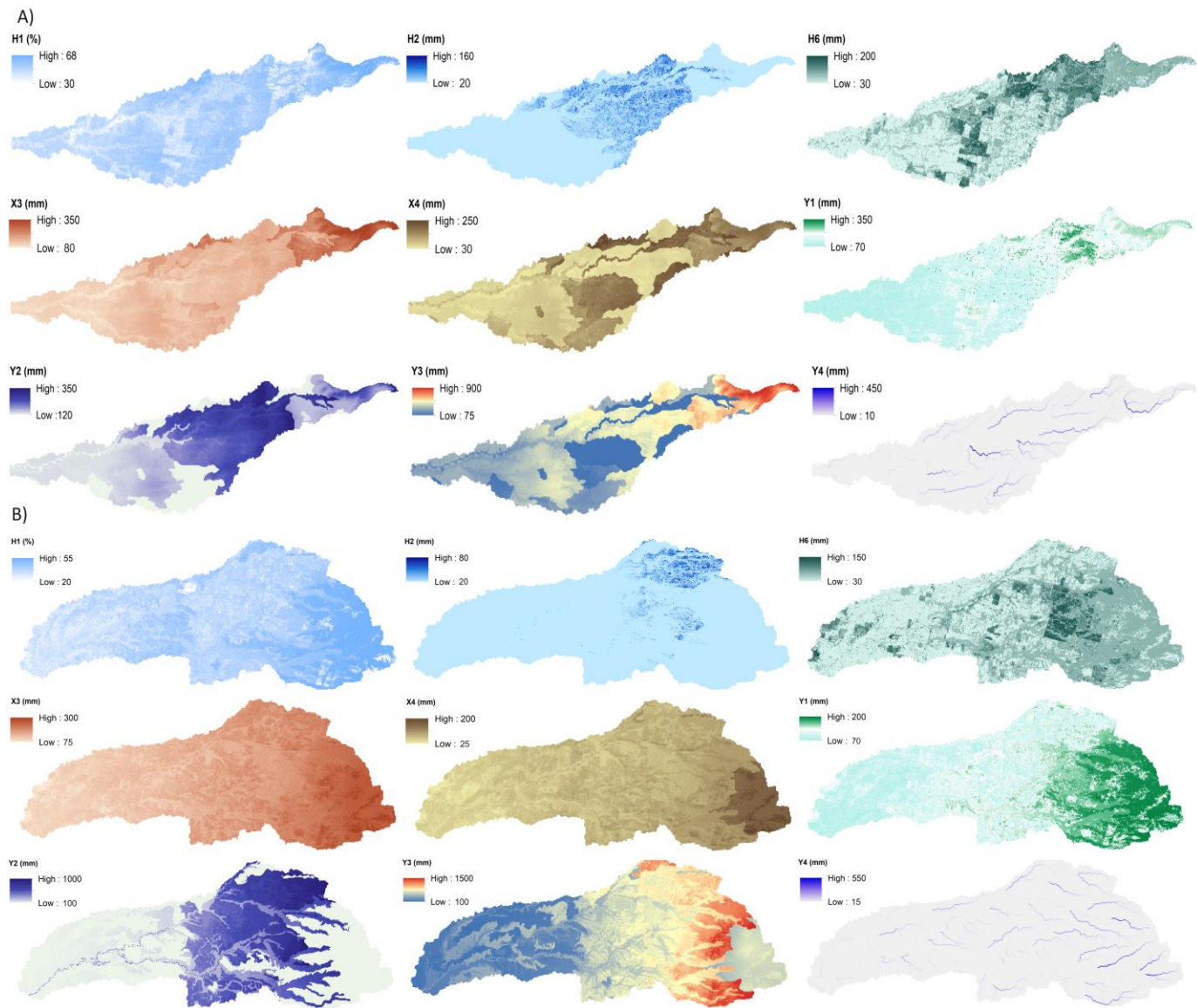


Fig. 5. Hydrological processes annual spatial distribution (A) Quino and (B) Muco Basin. Seasonal periods: 1980-2018. Soil moisture (H1), Surface storage (H2), Vegetative cover storage (H6), Infiltration (X3), Percolation (X4), Evapotranspiration (Y1), Runoff (Y2), Interflow (Y3) Base flow (Y4).

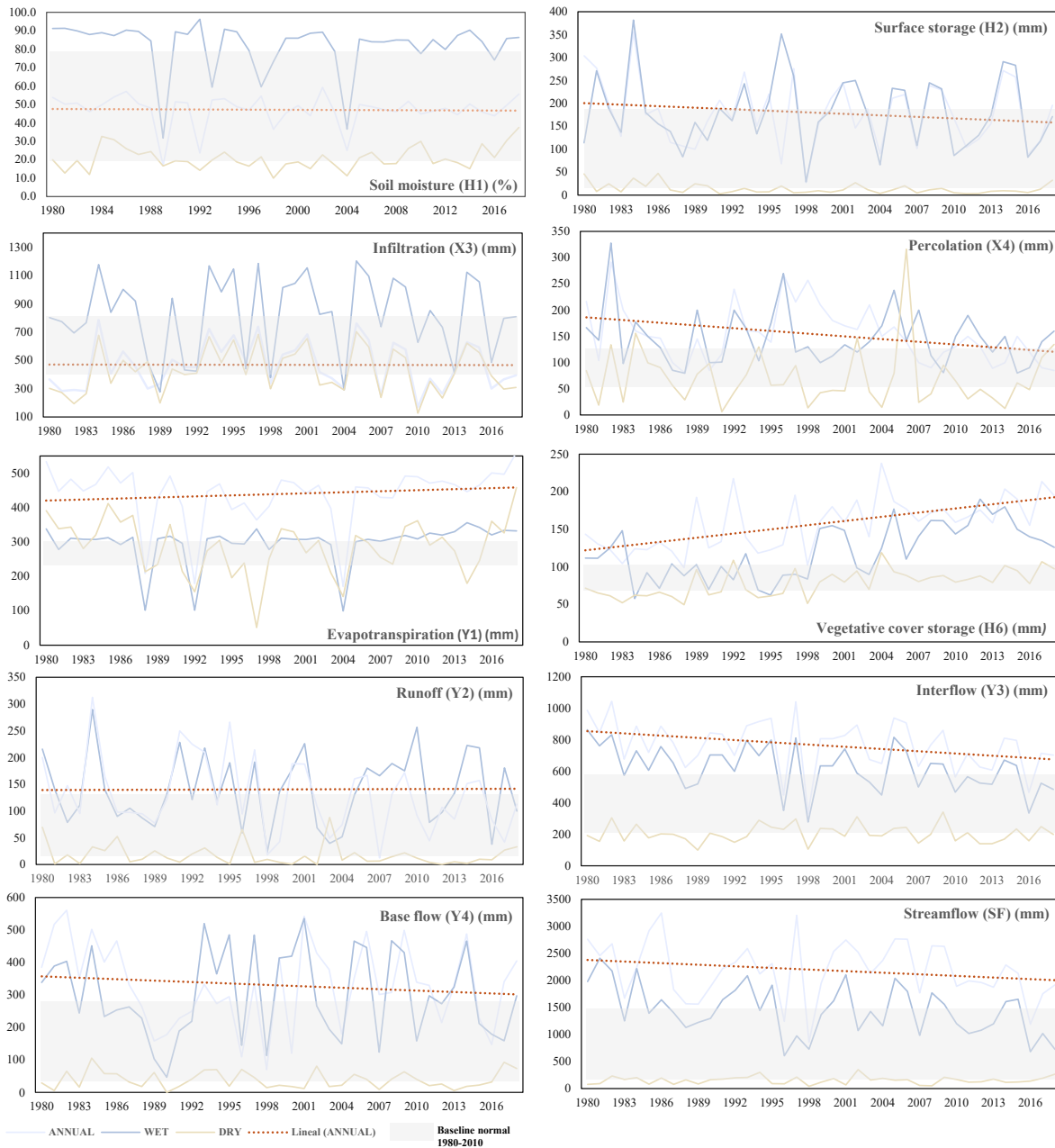


Fig. 6. Hydrological processes and streamflow, annual, wet and dry mean season (1980-2018).

3.2. Correlation between landscape metrics and hydrological processes

During the annual and rainy period, the highest negative significant correlations are observed, particularly in relation to croplands and the CONT index. These correlations are associated with various hydrological processes, including vegetative cover storage, infiltration, percolation, evapotranspiration, and base flow. Meanwhile, NP demonstrated significant

positive correlations with streamflow. This finding suggests that the increased spatial contiguity at the class level in cultivated lands exerts an influence on the reduction of hydrological processes such as infiltration and percolation. Conversely, the tendency for a decline in the number of agricultural soil patches is associated with a decrease in streamflow within the basin. Young plantations exhibited a substantial negative correlation between the ECON index and key hydrological processes, including infiltration, percolation, evapotranspiration, and baseflow. In contrast, mature plantations exhibited significant negative correlations with ECON and evapotranspiration, along with significant positive correlations between CONT, PROX, and vegetative cover storage during annual and wet periods. In contrast, mature plantations exhibited a modest inverse correlation between their proximity to these patches and the infiltration, percolation, and baseflow regime during the dry season. Native forests demonstrated a positive relationship between CONT and NP and various hydrological processes, including infiltration, percolation, evapotranspiration, and streamflow. Conversely, negative correlations were observed between CWED, ECON, and vegetative cover storage and evapotranspiration, particularly during the annual and wet periods. Shrubland LUCCs, the ENN index (with evapotranspiration), CONT (with infiltration), and NP (with streamflow) exhibited significant positive correlations. The rise in ENN suggests an expansion in the distance between nearest neighbors at the patch level, while a decline in NP indicates a fragmentation of the shrubland landscape. A notable positive correlation has been identified between grasslands and the ENN index, as well as percolation, evapotranspiration, and baseflow, and NP with streamflow. At the landscape level, a significant negative correlation has been observed between the PD, DIV, and SHDI indices and vegetative cover storage, infiltration, percolation, evapotranspiration, and interflow during the annual and wet period (Figs. 7A and 8A). Given that the strongest correlations between landscape patterns, hydrological processes, and streamflow were observed for crops, young plantations, and native forests, an analysis of standardized coefficients by seasonal period was conducted. The objective of this analysis was to ascertain which predictor (landscape metrics) exerted a more substantial influence on hydrological processes and streamflow. (Fig. 7B and 8B). The analysis revealed that cropland, with the CONT index, exhibited the strongest response in the spatial behavior of infiltration, percolation, and evapotranspiration. Notably, NP exhibited a positive correlation with streamflow during the

annual period. Young plantation LUCC demonstrates significant values during the annual and wet periods; the greatest negative impact is observed with the ECON index and infiltration, percolation, and evapotranspiration. For native forests, the highest values are found for CONT and infiltration, percolation, and evapotranspiration. The NP metric demonstrates a notable response in streamflow behavior. Conversely, during the dry period, these values were considerably lower. In terms of landscape metrics, the most significant inverse influence on the response of hydrological processes is exerted by PD and SHDI, as evidenced by the behavior of vegetative cover storage, infiltration, percolation, and evapotranspiration.

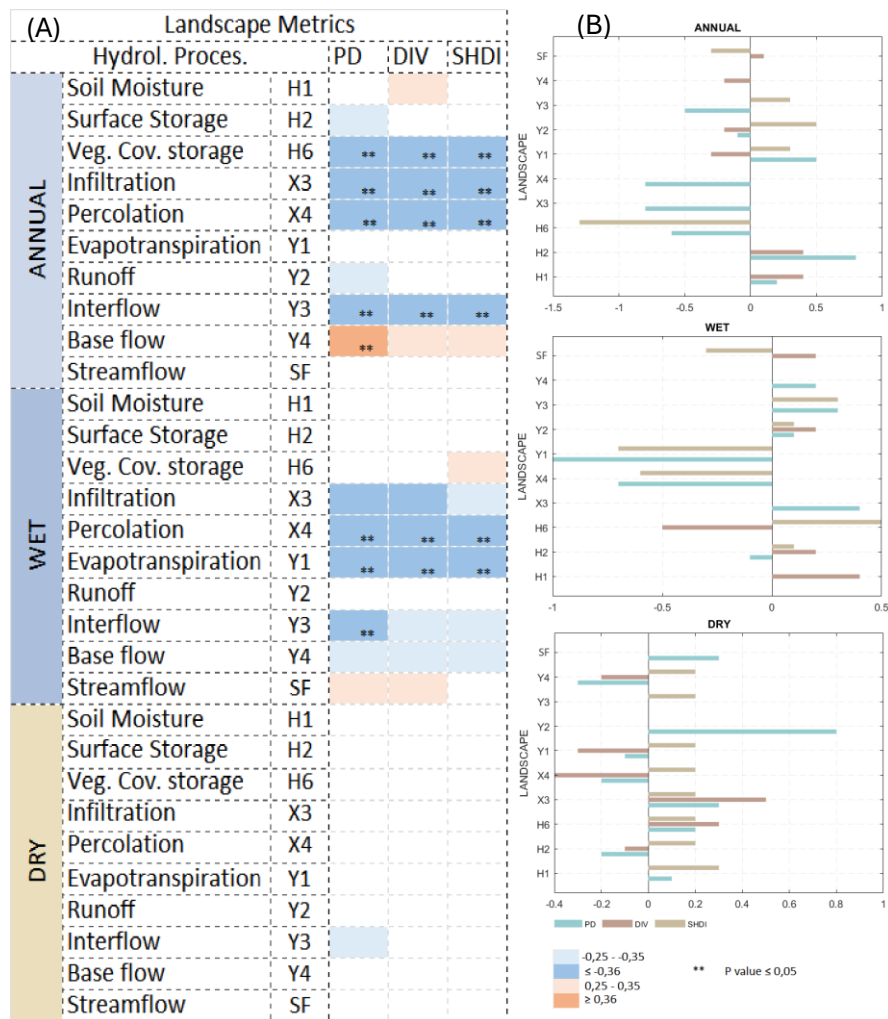


Fig. 7. (A). Pearson correlation between hydrological processes (HP) and streamflow (SF). (B). Standardized coefficient for HP and SF. Landscape level. Seasonal periods (1980-2018). Patch Density (PD), Landscape division index (DIV), Shannon's Diversity Index (SHDI).

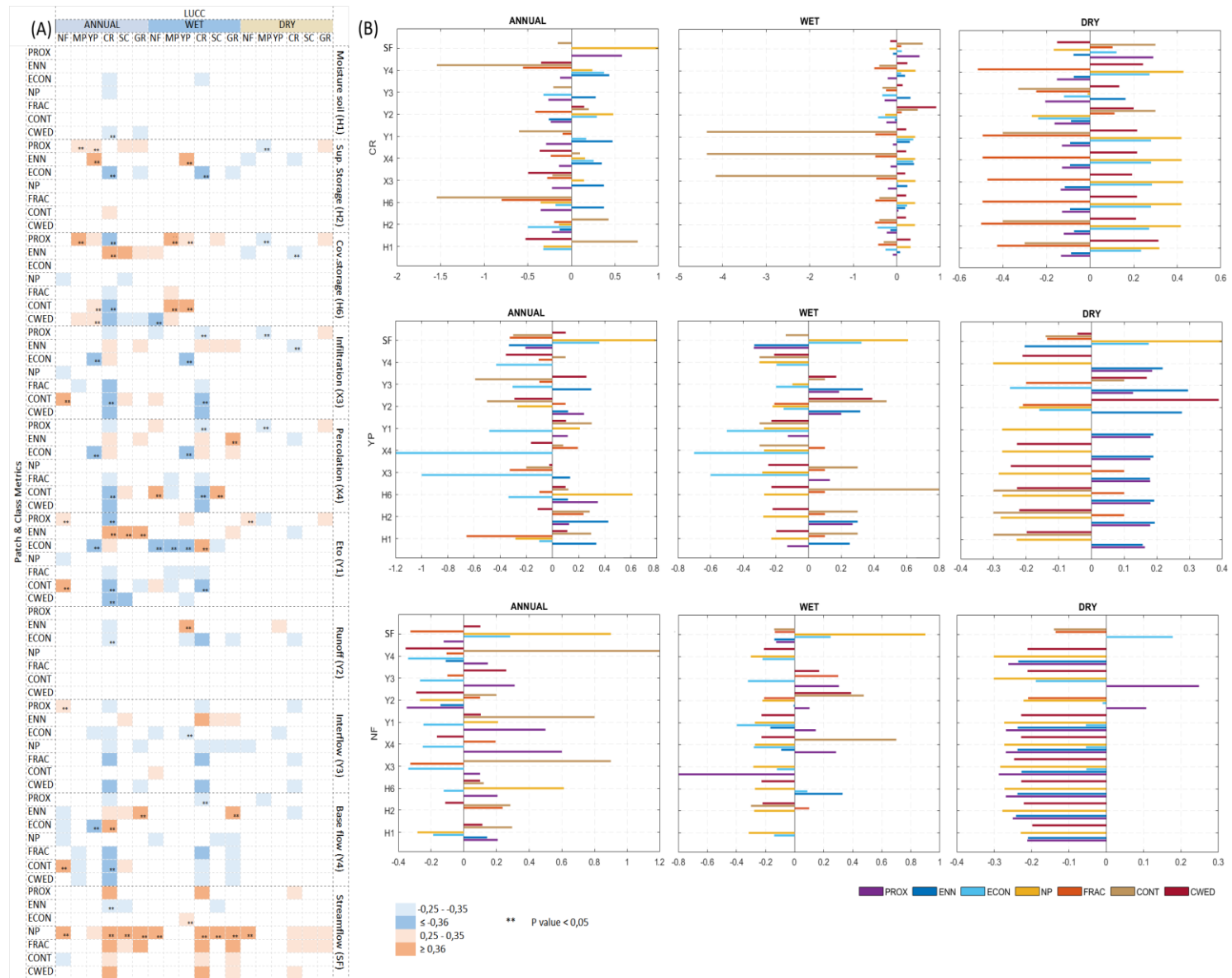


Fig. 8. (A) Pearson correlation for Hydrological processes & Streamflow. (B) Standardized coefficient for Hydrological processes & Streamflow. Patch & Class level. Native Forests (NF), Mature Plantations (MP), Young Plantations (YP), Crops (CR), Shrubland (SC), Grassland (GR). Proximity Index (PROX), Euclidean Nearest-Neighbor Distance (ENN), Edge Contrast Index (ECON), Number of Patches (NP), Fractal Dimension Index (FRAC), Contiguity Index (CONT), Contrast Weighted Edge Density (CWED). Seasonal periods (1980-2018).

A partial least squares regression (PLSR) analysis for seasonal periods, combining hydrological processes as a single dependent variable and streamflow as another dependent variable, indicates that the first and second components are the most effective in explaining the variation in the response of hydrological processes and streamflow under the influence of landscape metrics. Specifically, the second component accounts for the largest percentage of the observed behavior, particularly for the class metrics associated with young plantations, with values ranging from 71 to 68%. The estimated Q^2_{cum} for this component is 0.65 and 0.45, respectively, representing the highest and lowest values observed for the hydrological processes in the dry and rainy seasonal periods (see Table 5). Young plantations demonstrate the highest variable importance in projection (VIP) values in conjunction with the NP metric, specifically for the streamflow (VIP=3.46, W=0.57) and hydrological process (VIP=2.35, W=0.57) during the humid and annual periods, respectively. Subsequently, native forests with streamflow (VIP=2.76, W=0.63) and crops with hydrological processes (VIP=2.18, W=-0.73) were identified, with NP and ECON, for the humid period. The values that equaled VIP to 0 were associated with the CWED metric, specifically for shrub LUCC and hydrological processes in the wet period, and mature plantation for streamflow in the dry period. The metric that demonstrated the highest VIP values was NP, followed by ENN. The seasonal period with the highest VIP is the annual period, followed by the humid period. In the context of landscape metrics, the SHDI metric exhibited the highest value for streamflow (VIP=1.84, W=0.40) during the dry period (refer to Table S.2 in the supplementary material).

Table 5.
Summary of the PLSR model for HP and SF, for each LUCC.

			Q² acum	R²Y acum	R²X acum		
ANNUAL	HP	Comp1	0	0.05	0.25	YOUNG PLANTATION	PATCH
		Comp2	0.45	0.12	0.7		
	SF	Comp1	0.08	0.21	0.17		
		Comp2	0.42	0.24	0.61		
WET	HP	Comp1	0.05	0.1	0.3	CROPS	
		Comp2	0.35	0.16	0.58		
	SF	Comp1	0.07	0.21	0.24		
		Comp2	0.3	0.26	0.52		
DRY	HP	Comp1	-0.02	0.08	0.18	CROPS	
		Comp2	0.45	0.11	0.7		
	SF	Comp1	0.03	0.1	0.19		
		Comp2	0.44	0.11	0.64		
ANNUAL	HP	Comp1	0.01	0.02	0.59	YOUNG PLANTATION	CLASS
		Comp2	0.6	0.08	0.7		
	SF	Comp1	-0.05	0.08	0.21		
		Comp2	0.55	0.1	0.67		
WET	HP	Comp1	0.02	0.04	0.49	YOUNG PLANTATION	
		Comp2	0.45	0.09	0.68		
	SF	Comp1	0.02	0.03	0.59		
		Comp2	0.43	0.08	0.68		
DRY	HP	Comp1	0	0.03	0.27	YOUNG PLANTATION	
		Comp2	0.65	0.05	0.71		
	SF	Comp1	-0.03	0.04	0.2		
		Comp2	0.62	0.04	0.71		
ANNUAL	HP	Comp1	0.08	0.12	0.35	LANDSCAPE	
		Comp2	0.4	0.17	0.52		
	SF	Comp1	0.22	0.32	0.32		
		Comp2	0.42	0.38	0.52		
WET	HP	Comp1	0.08	0.11	0.34		
		Comp2	0.43	0.17	0.5		
	SF	Comp1	0.19	0.29	0.31		
		Comp2	0.44	0.34	0.53		
DRY	HP	Comp1	0.03	0.05	0.35		
		Comp2	0.23	0.08	0.55		
	SF	Comp1	0.14	0.2	0.3		
		Comp2	0.2	0.23	0.54		

**HP: Hydrological Process, SF: Streamflow*

The graphs of the VIP values across seasonal periods demonstrate that the NP metric provides the most robust explanation for the variation in hydrological processes related to landscape patterns associated with young plantations. The greatest variations in the dry period are associated with PROX and crop soils. Conversely, it is evident that when hydrological processes are considered as a standalone variable, they exhibit a higher degree of variation when influenced by a multitude of dependent variables. With regard to streamflow, there is a stronger consensus on the metric that exerts the greatest influence on this variable's behavior. NP is identified as a crucial metric in elucidating the variance of streamflow across all seasonal periods. In the annual period with young plantations and in both wet and dry periods with native forests, NP emerges as a dominant metric. Among the landscape metrics, the variable of greatest and least importance is SHDI, with streamflow in the dry and wet periods, respectively (Figs. 9, 10A, 10B).

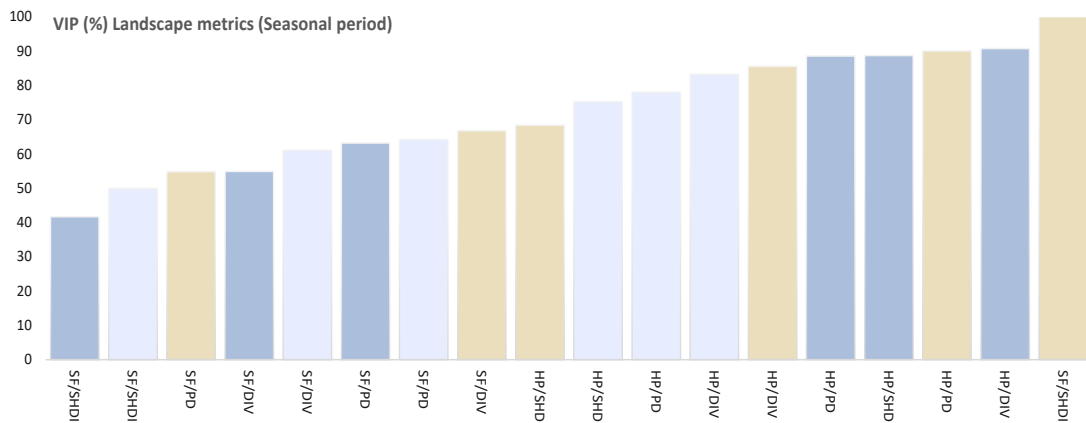


Fig. 9. Relative importance of landscape metrics (VIP) (%). Patch Density (PD), Landscape division index (DIV), Shannon's Diversity Index (SHDI). Hydrological Process (HP), Streamflow (SF).

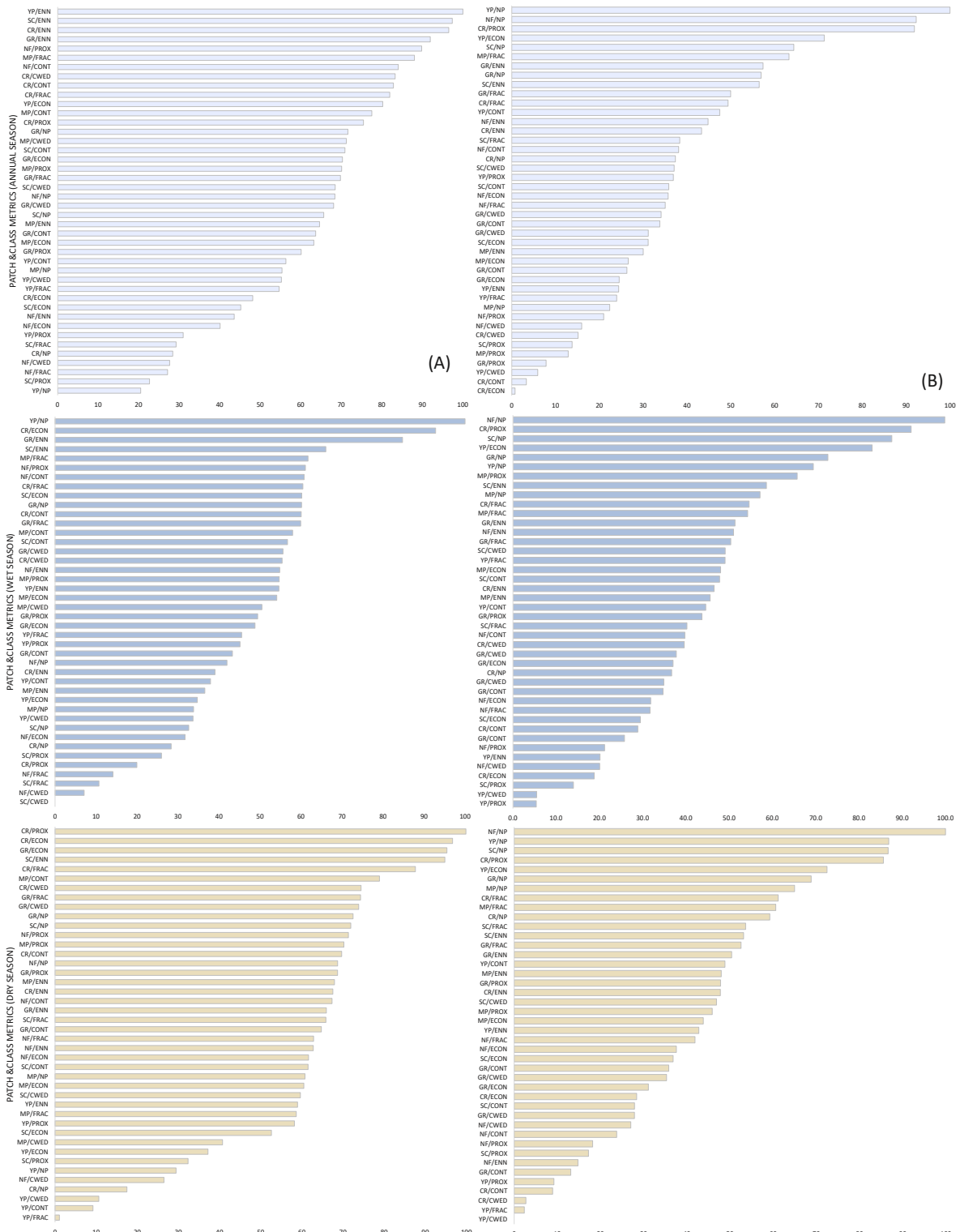


Fig. 10. (A) Relative importance of Patch & Class on Hydrological Processes (VIP) (%). (B) Relative importance of Patch & Class on Streamflow (VIP) (%). Native Forest (NF), Mature Plantation (MP), Young Plantation (YP), Crops (CR), Shrubland (SC), Grassland (GR). Proximity Index (PROX), Euclidean Nearest-Neighbor Distance (ENN), Edge Contrast Index (ECON), Number of Patches (NP), Fractal Dimension Index (FRAC), Contiguity Index (CONT), Contrast Weighted Edge Density (CWED).

4. Discussion

4.1. Performance of the TETIS Hydrological Model

The performance metrics of the TETIS model (i.e., NSE, PBIAS, and RSR) show a very good level of fit between observations and simulations according to the guidelines established by (Moriasi et al., 2007). Furthermore, the evaluation criteria from (Moriasi et al., 2015) indicate very good performance for $NSE > 0.80$ and $PBIAS \leq \pm 10$. Therefore, the model performs very well in almost all cases (Table 4), as evidenced by the findings of other studies in the region. For example, (Martínez-Retureta et al., 2020a), applying the SWAT model at a monthly time scale, found 0.84 and 0.79 in the Quino basin and NSE values of 0.88 and 0.89 in the Muco basin, during calibration and validation, respectively. On the other hand, the model also performs notably better in relation to other studies in the region. For example, Barrientos et al. (2020) applied the TETIS model at a daily time scale in experimental basins of the Biobío Region with areas between 7 and 414 ha and found values of $-0.2 < NSE < 0.6$ and $-17.3 < NSE < 0.3$ for calibration and validation, respectively. These findings collectively suggest that the TETIS model was effectively calibrated and validated at a daily time scale for the present study. It is crucial to emphasize that Chile is a mountainous country with a limited number of meteorological stations, particularly above 1000 MASL, which poses significant challenges to climate estimation (Benra et al., 2021). A notable aspect of TETIS is the FC2 factor (evapotranspiration), where values greater than 2 were observed. Given the temperate Mediterranean climate, with relatively low temperatures during the year (10.0°C), it is plausible that these high values of evapotranspiration may be associated with the characteristics of soil types. Soils with good water retention capacity can increase evapotranspiration rates (Berg et al., 2014). This is particularly relevant given the prevalence of silty loam soils (Andisol and Inceptisol) in both basins, which are known for their high-water retention capacity (Roa García et al., 2021). Another key factor influencing these rates is the type of vegetation present in the basins. A significant proportion of the territory is covered by forest plantations, which has a substantial impact on evapotranspiration (Balocchi et al., 2023; Oyarzún, 1999; White et al., 2021). (White et al., 2021) reported cumulative annual values of 400 mm/year for basins in the region, particularly in areas with forest plantations. (Balocchi et al., 2023; Oyarzún, 1999) found values between 600-400 mm/year and 600-300 mm/year, respectively. In the case of the Quino basin, which required greater adjustment in the evapotranspiration corrective factor, the highest cumulative annual values are 350 mm/year, coinciding with the areas where forest plantations prevail in the basin.

4.2. Landscape Pattern (configuration & composition). Implications on the water cycle.

Since 1986, croplands have been concentrated in the lower-middle portions of the landscape (see Fig. S.1-2 in the supplementary material), characterized by aggregated and interconnected patches. This simplified landscape has become dominant in the region, replacing native forests, shrublands, and grasslands (Fig. 11). The spatial continuity of this homogeneous agricultural landscape exerts a substantial influence on hydrological processes, followed closely by a reduction in the number of patches (NP), which significantly impacts streamflow. Some studies suggest that croplands enhance water production (Aygün et al., 2022; Yohannes et al., 2021), and our findings align with this, particularly regarding the NP metric, as a decrease in the number of patches results in water losses at basin outlets, especially during the wet season. Notably, Yohannes et al. (2021) explored the sub-basin scale, proving significant correlations between metrics such as the Largest Patch Index (LPI) and the Percentage of Landscape (PLAND) with water availability; however, area metrics were excluded as they did not exhibit significant relationships in our research.

Forest plantations have expanded within the watersheds, replacing native forests, agricultural areas, and shrublands (Fig. 11; see Fig. S.1-2). Among the landscape metrics analyzed, the Edge Contrast Index (ECON) exhibited the strongest negative correlation with hydrological processes and young plantations. A loss of diversity or heterogeneity in landscape structure at the patch level has been associated with increased evapotranspiration. This observation aligns with the findings of (White et al., 2021), who reported elevated evapotranspiration rates in *Eucalyptus globulus* and *Pinus radiata* plantations compared to native forests in Chile. Mature plantations exhibited a strong positive correlation with the PROX and CONT metrics, associated with vegetative cover storage, consistent with findings by (Balocchi et al., 2023) and (Huber et al., 2010a). However, during the dry season, the PROX metric exhibited a significant negative correlation with hydrological processes. This seasonal behavior may be indicative of increased radial growth in forests driven by favorable climatic conditions, enhancing soil moisture retention and promoting vegetative expansion, which subsequently reduces hydrological processes such as infiltration (Camarero et al., 2022). Since the early 2000s, there has been a significant decline in native forest cover, primarily due to agricultural expansion and forestry activities (see Fig. 11 and Fig. S.1-2). This decline has increased fragmentation and reduced spatial connectivity (CONT) within native forests, negatively

affecting hydrological processes. Additionally, increased patch contrast has led to a reduction in evapotranspiration rates. At the class level, the fragmented structure of native forests impairs streamflow, while at the patch level, disaggregation reduces runoff. These findings align with studies emphasizing the adverse effects of native forest loss on the hydrological cycle (Haas et al., 2022; Lyu et al., 2023; Martínez-Retureta et al., 2020; Renée Brooks et al., 2010).

Shrublands dominate the lower basins, forming a fragmented landscape, while grasslands are more aggregated in central areas (see Fig. S.1-2; Table 1). Shrubland expansion has occurred at the expense of native forests, agricultural lands, and grasslands, whereas grassland contraction has been driven by the encroachment of crops and shrublands (Fig. 11). The ENN and NP metrics indicate increased fragmentation and reduced connectivity in shrublands, leading to higher evapotranspiration and lower streamflow. Further investigation is necessary to understand the effects of shrublands on water cycle components. Recent reviews emphasize the limited research that quantifies the effects of shrublands on ecosystem services (Smith-Ramírez et al., 2023). Grasslands, as indicated by ENN and NP metrics, show the most significant correlations with hydrological processes and streamflow. These metrics demonstrate increasing trends, reflecting patch expansion but with greater disaggregation, which enhances hydrological processes and streamflow at sub-basin outlets. These results are consistent with studies by Smith-Ramírez et al. (2023) showing that grassland areas contribute to reduced water flow and production.

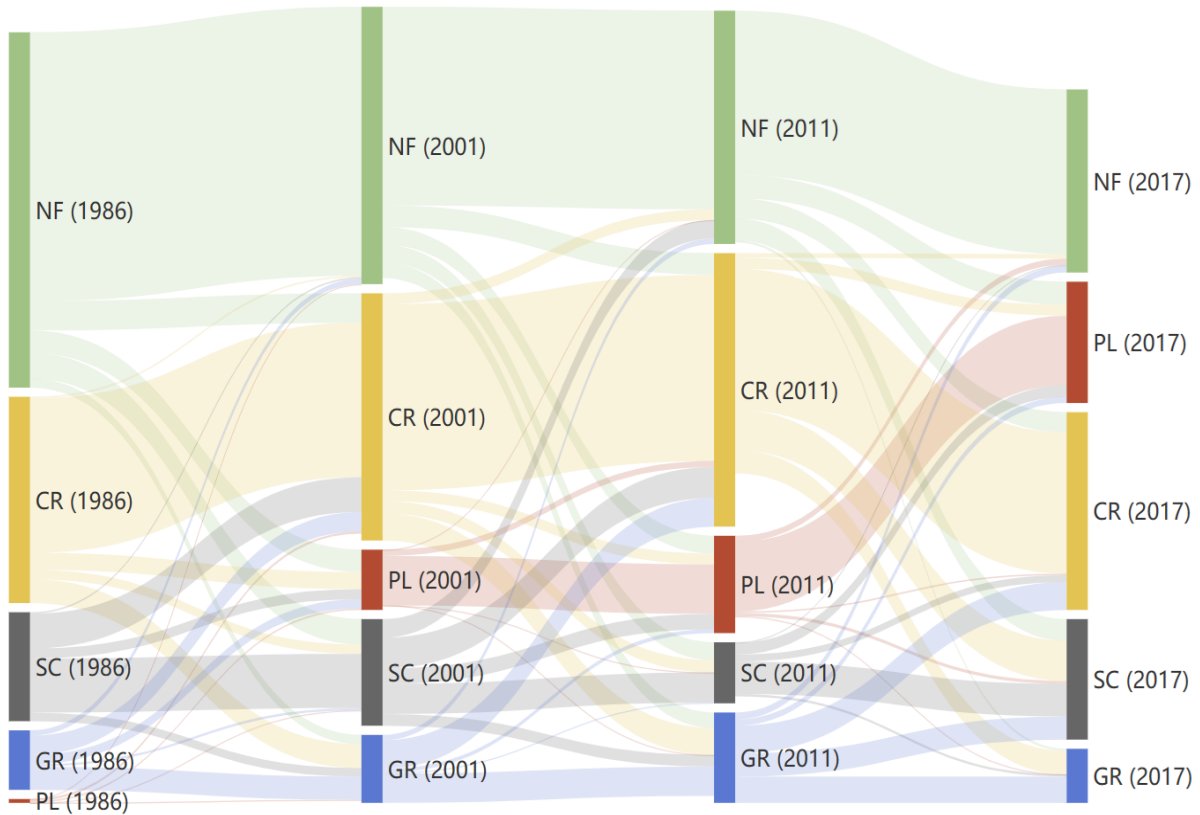


Fig. 11. Quino and Muco basins LUCC distribution (km²): 1986, 2001, 2011, 2017. Native forest (NF), Plantation (PL), Crop (CR), Shrubland (SC), Grassland (GR).

This study found that aggregation metrics demonstrated the strongest relationships with hydrological processes and streamflow dynamics. These metrics quantify the spatial tendencies of patch types to aggregate, disperse, and intersperse (J. Liu et al., 2020). Among these metrics, the Euclidean Nearest Neighbor (ENN) metric demonstrated the most significant associations with patch-level hydrological processes, particularly vegetative cover storage, evapotranspiration, and runoff. ENN achieved the highest Variable Importance in Projection (VIP) scores, highlighting its explanatory power for hydrological dynamics. ENN has been widely adopted as a simple measure of patch isolation in various studies, including soil evolution, plant species distribution, and the effects of landscape patterns on ecosystem services at the watershed level (A. Arora et al., 2021; Y. Cao et al., 2023; Li et al., 2021). The Number of Patches (NP) metric exhibited a notable positive correlation with streamflow across diverse land uses and covers (LUCC), encompassing native forests, croplands, shrublands, and grasslands. NP also ranked highly in VIP scores, emphasizing its role in explaining streamflow variability. Previous studies have leveraged NP to explore its relationships with storm runoff, water availability, sedimentation regimes, and water

displacement in agricultural soils (Y. Han et al., 2021; Yohannes et al., 2021; G. Zhang et al., 2013).

The Edge Contrast (ECON) metric revealed significant patterns, particularly in forest plantations, where it influenced infiltration, percolation, and evapotranspiration. Shape metrics also showed a substantial influence on hydrological components. The Contiguity Index (CONT) is a metric that quantifies the spatial connectedness of cells within a patch to describe patch boundary configuration and shape (LaGro, 1991). It demonstrated strong correlations with croplands and native forests, affecting aquifer recharge and evapotranspiration. While the Fractal Index is more frequently used (H. Han et al., 2023; Y. Han et al., 2021; Li & Zhou, 2015; J. Liu et al., 2020; L. Sun et al., 2023), CONT has shown stronger relevance in these contexts. In contrast, the Fractal Index demonstrated limited utility beyond basic correlations in our research.

At the landscape scale, metrics highlighted the substantial loss of native forests. Landscapes with greater diversity, fragmentation, and patch density were linked to reductions in infiltration, percolation, and evapotranspiration. These findings underscore the critical role of aggregated and heterogeneous landscape configurations in shaping hydrological processes. However, this study found weak correlations between landscape metrics and streamflow, which contrasts with previous studies (J. Liu et al., 2020). These previous studies reported that diversity metrics significantly influence hydrological flows.

4.3. Application on watershed management and climatic adaptation strategies with the consideration of landscape patterns.

The development of legitimate, operational, and feasible landscape planning strategies for climate change adaptation relies on the interplay of various factors, including spatial patterns, cultural contexts, governance systems, socio-economic structures, planning methodologies, historical trajectories, and collectively envisioned futures (Galan et al., 2023). Landscape changes have a significant impact on hydrological ecosystem functions and services (Babaremu et al., 2024; Yohannes et al., 2021). Therefore, it is crucial to establish the relationships between the spatial structure of land use and cover change (LUCC) and the components of the water cycle. Landscape metrics play a pivotal role in integrating landscape planning with climate change adaptation strategies, thereby promoting sustainable watershed management. The interdisciplinary nature of this approach, combined with the varying

impacts of different landscape configurations and compositions across scales, makes it a complex adaptation strategy. The intricate relationship between spatial planning and property regimes adds another layer of complexity (Compton, 2024).

As demonstrated by these findings, conserving and restoring native forest cover is crucial for maintaining water resources in watersheds. Implementing forestry practices at the disaggregated surface levels can help preserve surface water storage, reduce edge contrast between patches, and mitigate increased evapotranspiration. Song et al. (2023) emphasize the importance of incorporating landscape metrics as a tool for climate change adaptation, highlighting that understanding changes in landscape patterns is essential for effective soil conservation strategies. The magnitude and direction of these impacts vary considerably across regions, requiring the development of spatially tailored adaptive landscape management strategies by policymakers. For example, while climate change may hinder the restoration of native vegetation in some areas, shrubs and grasslands have been proposed as suitable alternatives for managing dryland landscapes (S. Cao et al., 2011). A promising approach to evaluating the feasibility of such strategies involves designing new LUCC scenarios that combine composition and configuration, nature-based solutions, and basin-specific social factors. These scenarios should demonstrate how the water balance responds to these drivers. Given the intricate interplay between climate and landscape configurations on water balance elements like streamflow, an integrated assessment of climate and land-use scenarios is essential to comprehensively capture their impacts (L. Lyu et al., 2023).

5. Conclusions

The objectives of this research were twofold: first, to explore how landscape patterns affect the main hydrological processes, and second, to determine which landscape patterns have a higher impact on streamflow for the Quino and Muco basins located in the south-central region of Chile. The TETIS hydrological model was successfully employed to simulate the characteristics of the hydrological cycle in the two sub-basins on a daily time scale. Our research indicates a correlation between landscape aggregation, measured as the number of patches, and streamflow for both agricultural and native forest land uses. The shape and contiguity of the basins have a greater influence on the behavior of the infiltration and percolation capacity, as well as changes in the evapotranspiration regime. Conversely, the agricultural land use is associated with the contrast metric as ECON impacts the surface runoff

regime. The expansion of forest plantations has significant ramifications for hydrological processes. In the present study, the ECON metric is instrumental in establishing the relationship between increased infiltration, percolation, and evapotranspiration. These changes become more significant with the presence of young plantations. In the case of shrublands and grasslands, the ENN aggregation metric demonstrated the strongest relationships. The loss of both land uses has led to an increase in the behavior of hydrological processes, which are fundamentally associated with vegetative cover storage and evapotranspiration. It is then concluded that aggregation metrics have a considerable impact on the behavior of a significant portion of the water cycle variables, particularly during the rainy season. Furthermore, an aggregated landscape, characterized by increased adjacency between the edges of native forest classes and patches, enhances water transit, leading to increased recharge in aquifers and enhanced streamflow. These results are promising and could inform future composition and configuration restructuring for smaller scale basins in Chile. This research could contribute to increasing the resilience capacity in the context of nature-based solutions and water resources management within the region.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Supplementary Material.

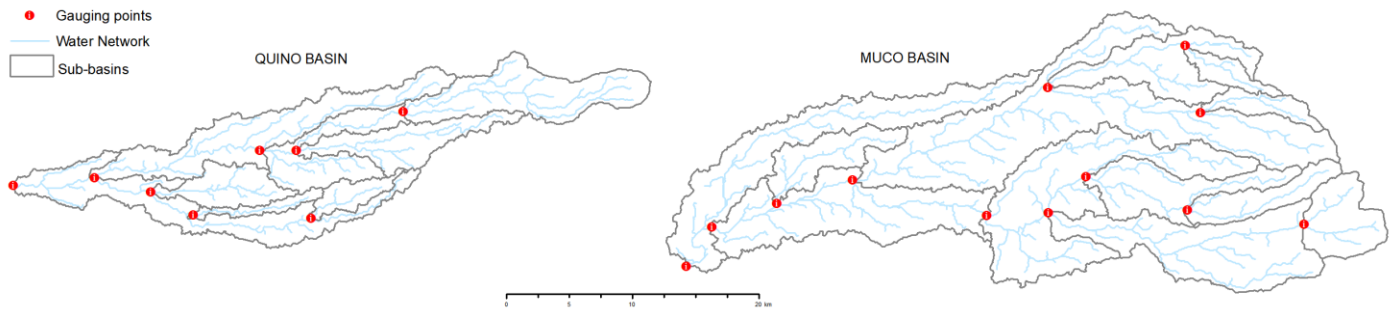


Fig. S.3. Sub-basins and gauging point Quino and Muco basins.

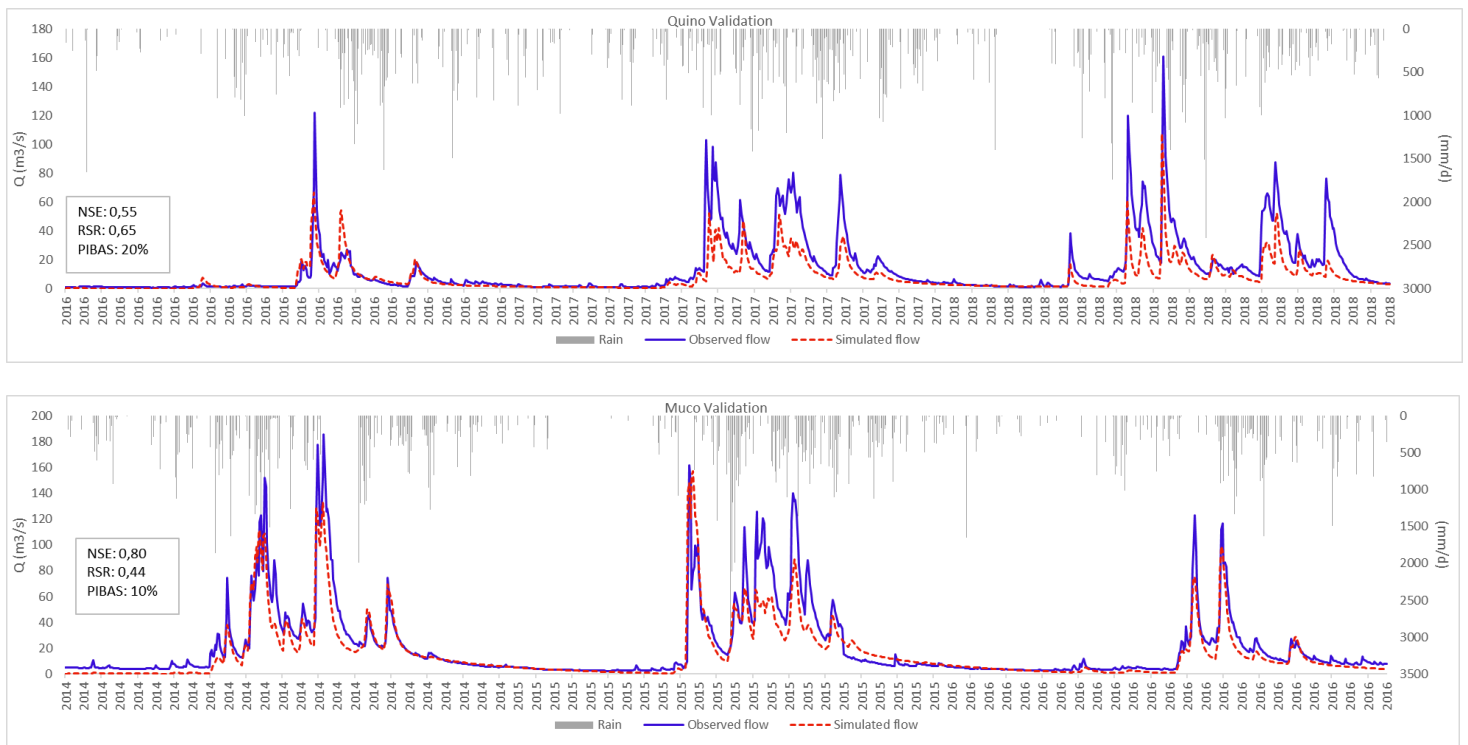


Fig. S.4. Quino Validation (2016-2018) - Muco Validation (2014-2016). Land use 2017.

Table S.2.

VIP and weight of landscape metrics for each land used. (Patch, Class) and Landscape scale. HP and SF.

METRIC	HP												
	NF		MP		YP		CR		SC		GR		
	VIP	W	VIP	W	VIP	W	VIP	W	VIP	W	VIP	W	
PROX	1.56	0.52	1.22	0.68	0.54	-0.18	1.31	-0.44	0.39	0.13	1.05	-0.35	ANNUAL
ENN	0.76	-0.25	1.12	-0.44	1.74	0.58	1.68	0.56	1.69	0.56	1.60	0.72	
ECON	0.70	-0.23	1.10	-0.48	1.40	-0.47	0.84	0.28	0.79	0.26	1.22	-0.41	
NP	1.19	-0.27	0.96	-0.22	0.36	0.08	0.49	-0.11	1.14	-0.26	1.25	-0.29	
FRAC	0.47	-0.11	1.53	-0.35	0.95	0.22	1.43	-0.33	0.51	-0.12	1.21	-0.28	
CONT	1.46	0.34	1.35	-0.31	0.98	0.22	1.44	-0.33	1.23	0.28	1.11	-0.25	
CWED	0.48	-0.11	1.24	-0.28	0.96	0.22	1.45	-0.33	1.19	-0.27	1.18	-0.27	
PROX	1.43	0.48	1.28	0.43	1.06	0.35	0.47	0.16	0.61	0.20	1.16	-0.39	WET
ENN	1.29	-0.43	0.86	-0.29	1.28	-0.43	0.92	-0.31	1.55	-0.52	1.99	0.66	
ECON	0.74	-0.25	1.27	0.42	0.81	-0.27	2.18	-0.73	1.41	0.47	1.15	0.38	
NP	0.98	-0.23	0.79	0.18	2.35	0.57	0.67	-0.15	0.77	-0.18	1.41	-0.32	
FRAC	0.33	-0.08	1.45	0.33	1.07	0.25	1.42	-0.33	0.25	-0.06	1.41	-0.32	
CONT	1.43	0.33	1.36	0.31	0.89	0.00	1.41	-0.32	1.33	0.31	1.02	-0.23	
CWED	0.17	-0.04	1.19	0.27	0.79	0.16	1.30	-0.30	0.00	-0.18	1.31	-0.30	
PROX	1.35	0.45	1.33	0.44	1.10	-0.37	1.89	-0.63	0.61	-0.20	1.30	-0.43	DRY
ENN	1.19	-0.40	1.28	-0.43	1.11	0.37	1.28	0.43	1.79	0.60	1.25	-0.42	
ECON	1.16	0.39	1.14	0.38	0.70	0.23	1.83	0.61	0.99	-0.33	1.80	-0.65	
NP	1.30	-0.30	1.15	-0.26	0.56	-0.13	0.33	-0.08	1.36	-0.35	1.37	-0.31	
FRAC	1.19	-0.14	1.11	-0.25	0.02	0.00	1.66	-0.38	1.24	-0.38	1.40	-0.32	
CONT	1.27	0.32	1.49	-0.34	0.17	0.04	1.32	-0.30	1.16	-0.12	1.22	-0.28	
CWED	0.50	-0.11	0.77	-0.18	0.20	-0.05	1.41	-0.32	1.13	-0.37	1.39	-0.32	
	SF												
PROX	0.61	-0.20	0.37	-0.12	1.07	-0.36	2.66	0.89	0.40	0.13	0.23	0.08	ANNUAL
ENN	1.30	0.43	0.87	0.29	0.71	-0.24	1.26	-0.42	1.64	-0.55	1.66	-0.55	
ECON	1.04	0.35	0.77	-0.26	2.07	0.69	0.02	0.01	0.90	0.30	0.71	0.24	
NP	2.68	0.87	0.65	0.25	3.46	0.79	1.08	0.26	1.87	0.52	1.65	0.64	
FRAC	1.02	0.27	1.83	0.42	0.69	0.25	1.43	0.37	1.11	0.26	1.45	0.13	
CONT	1.10	0.09	1.38	0.32	0.10	0.21	1.04	0.06	0.76	0.21	0.98	0.11	
CWED	0.46	0.01	0.17	0.04	0.44	0.22	1.07	-0.22	0.99	0.26	0.90	-0.14	
PROX	0.58	-0.19	1.81	-0.60	0.15	0.05	2.54	0.85	0.39	0.13	1.21	0.40	WET
ENN	1.41	0.47	1.26	-0.42	0.56	-0.19	1.28	-0.43	1.62	-0.54	1.42	-0.47	
ECON	0.88	0.29	1.32	-0.44	2.29	0.76	0.52	0.17	0.81	0.27	1.02	0.34	
NP	2.76	0.63	1.58	0.36	1.92	-0.62	1.01	-0.22	2.42	0.55	2.01	0.46	
FRAC	0.88	0.20	1.50	0.34	1.35	-0.12	1.51	-0.35	1.11	0.25	1.39	0.32	
CONT	1.10	-0.25	1.23	0.28	0.80	0.16	1.32	-0.30	0.71	-0.16	0.96	0.22	
CWED	0.55	0.13	0.15	-0.07	1.09	-0.10	1.35	-0.31	0.96	0.22	1.04	0.21	
PROX	0.50	0.25	1.26	0.42	0.25	0.08	2.35	0.78	0.47	0.16	1.31	0.44	DRY
ENN	0.41	-0.14	1.32	0.44	1.18	-0.39	1.31	-0.44	1.46	-0.49	1.39	-0.46	
ECON	1.03	0.34	1.20	0.40	1.99	0.66	0.78	0.26	1.01	0.05	0.86	0.29	
NP	2.75	0.63	1.79	0.41	2.39	0.55	1.63	0.37	2.38	0.37	1.89	0.56	

FRAC	1.15	0.00	1.67	0.38	0.06	0.01	1.68	0.39	1.47	0.39	1.45	0.33
CONT	0.65	-0.15	1.34	0.23	0.25	-0.06	0.77	0.18	0.36	-0.08	0.98	0.23
CWED	0.74	0.17	0.00	-0.02	0.07	0.02	1.29	0.30	0.77	0.18	0.97	0.22
	ANNUAL			WET			DRY					
	PD	DIV	SHDI	PD	DIV	SHDI	PD	DIV	SHDI			
VIP	1.44	1.53	1.38	1.63	1.67	1.63	1.66	1.57	1.26	HP	LANDSCAPE	
W	-0.35	-0.35	-0.33	-0.35	0.14	0.21	-0.35	-0.33	-0.26			
VIP	1.18	1.12	0.92	1.16	1.01	0.77	1.01	1.23	1.84	SF		
W	0.25	0.23	0.19	0.30	0.29	0.28	0.34	0.31	0.40			

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CAPÍTULO V. EVALUATING THE EFFECTS OF LARGE-SCALE REFORESTATION AND CLIMATE CHANGE ON WATER CYCLE DYNAMICS IN TWO BASINS OF SOUTH-CENTRAL CHILE

Resumen.

Los bosques desempeñan un papel fundamental en la regulación del ciclo hidrológico y en la provisión de servicios ecosistémicos esenciales, funciones que están siendo cada vez más amenazadas por los efectos del cambio climático y las actividades humanas. En este contexto, Chile se presenta como un caso particularmente relevante para estudiar la relación entre el cambio en el uso del suelo y los procesos hidrológicos, debido a su historia de transformaciones del paisaje impulsadas por prácticas de manejo insostenible del territorio y el creciente estrés hídrico en su zona centro-sur. Este estudio se enfocó en analizar los efectos de la restauración forestal sobre los procesos hidrológicos bajo un escenario climático futuro (RCP8.5). Para ello, se simularon cuatro escenarios de reforestación utilizando el modelo hidrológico TETIS. Estos escenarios fueron diseñados en base a políticas nacionales de restauración y metodologías como las Soluciones Basadas en la Naturaleza (NBS), políticas ambientales y criterios socioeconómicos, y se aplicaron a dos subcuencas del río Imperial, ubicado en la Región de La Araucanía. El objetivo principal fue evaluar cómo la restauración forestal, aplicada a diferentes escalas espaciales, puede influir en los procesos hidrológicos y en el balance hídrico, incluso ante un contexto de disminución proyectada en las precipitaciones debido al cambio climático. Los resultados obtenidos muestran que la combinación del cambio climático y el cambio en el uso del suelo es el principal factor que explica la mayor variación porcentual en los procesos hidrológicos. Se observó que el aumento de la cobertura forestal conduce a una mayor evapotranspiración, especialmente en escenarios donde la reforestación se basa en plantaciones exóticas. Esto tiende a generar una disminución del caudal, afectando la disponibilidad hídrica, especialmente durante los períodos secos. Sin embargo, se identificó que aquellos escenarios donde la restauración de bosques nativos se concentra en las zonas medias y altas de las cuencas presentan un efecto amortiguador sobre el caudal, ayudando a mantener ciertos niveles de flujo durante la estación seca. En términos del balance hídrico, la restauración a gran escala con especies nativas mejora la capacidad de retención de agua, lo cual puede ser beneficioso para enfrentar eventos de sequía. Por el contrario, las mayores pérdidas dentro del balance de agua se producen en escenarios dominados por plantaciones exóticas, especialmente en años con menor disponibilidad de precipitaciones. Los resultados de este estudio subrayan la importancia de considerar tanto el

tipo de cobertura forestal como su localización dentro de las cuencas al diseñar estrategias de restauración. La restauración con especies nativas no solo contribuye a conservar la biodiversidad, sino que también puede desempeñar un papel clave en la gestión sostenible del agua en regiones vulnerables al cambio climático como el sur de Chile.



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Abstrac:

Forests play a fundamental role in regulating the hydrological cycle and providing essential ecosystem services functions increasingly threatened by the impacts of climate change and human activities. Chile represents a particularly relevant case for examining the relationship between land use change and hydrological processes, given its history of landscape transformations driven by unsustainable land management practices and the growing water stress in its south-central region. Under the RCP8.5 climate scenario, four reforestation scenarios were simulated using the TETIS hydrological model. These scenarios were developed based on national policies and restoration methodologies such as Nature-Based Solutions (NBS) and social criteria and were applied to two sub-basins of the Imperial River

in the Araucanía Region. The objective was to evaluate the effects of forest restoration at different spatial scales on hydrological processes and water balance, despite projected decreases in precipitation. Our findings indicate that the combined effects of climate change and land use change produce the greatest percentage of variation in hydrological processes. Increases in forest cover lead to higher evapotranspiration, particularly when reforestation involves exotic plantations. Although streamflow's generally decline, scenarios in which native forest restoration is concentrated in the mid-to-upper sections of the basins show a buffering effect on streamflow, especially during the dry season. Regarding the water balance, large-scale native forest restoration results in greater water retention, whereas the greatest losses occur under reforestation scenarios dominated by exotic plantations, particularly during dry years.

1. Introducción

Launched in June 2021, the United Nations Decade on Ecosystem Restoration represents a global initiative aimed at the protection and revitalization of ecosystems for the benefit of both people and nature (United Nations Decade on Ecosystem Restoration, 2022). Among the top global priorities for restoration are native forest ecosystems (Bukoski et al., 2022; Wang et al., 2024). Forests play a vital role in regulating the hydrological cycle, ensuring water availability for both ecosystems and human populations. These efforts are of great relevance, as the future of forests and the hydrological processes they sustain remains highly uncertain due to climate change-related disturbances such as wildfires, droughts, hurricanes, sea level rise, increasing temperatures, and changes in the amount, seasonality, and form of precipitation (Wei et al., 2024). The intensification of the atmospheric water cycle, driven by elevated water vapor content, has exacerbated climatic extremes making arid regions drier and humid regions wetter. This shift has disrupted ecosystem functioning and the delivery of ecosystem services and is now considered a major driver of declining water provisioning services at the watershed scale (Li et al., 2023; Wang et al., 2023; Zhu et al., 2023; Maar et al., 2024). Moreover, the increasing scale of human activities has significantly amplified impacts on hydrological processes. Landscape transformations largely driven by land use change have resulted in the reduction of wetland areas and an increase in water demand due to the expansion of agricultural and urban sectors (Lu et al., 2023). Poorly managed land use and land cover changes have also altered surface runoff, groundwater dynamics, percolation, and lateral flows, thereby exacerbating water scarcity in many watersheds (Hernández et al.,

2024). Indeed, Bispo et al. (2023) identify land use and cover change as the primary anthropogenic driver impacting natural ecosystems, with direct consequences for the provision of ecosystem services. An alternative approach to assessing the impacts of land use changes on components of the water cycle involves the use of landscape metrics. Several studies have demonstrated strong associations between landscape metrics and alterations in erosion and sedimentation patterns within hydrographic basins. Key metrics include the Shannon Diversity Index, Aggregation Index, Largest Patch Index, Contagion Index, Patch Cohesion Index, and Number of Patches (Da Silva et al., 2015; Shi et al., 2013). Well-connected landscapes, in particular, play a critical role in reducing soil erosion (Jiang et al., 2020). Additionally, metrics related to area, shape, interception, and connectivity have been shown to influence surface runoff, baseflow, and percolation dynamics (Boongaling et al., 2018; Frey et al., 2021). Hernández et al. (2024) demonstrated that the contiguity and shape of landscape patches significantly influence infiltration and percolation capacity, as well as variability in evapotranspiration regimes particularly in regions experiencing the expansion of forest plantations. Their findings also highlighted the substantial influence of aggregation metrics on a wide range of hydrological variables, with particularly pronounced effects during the rainy season. For instance, a reduction in the number of natural forest patches was strongly correlated with diminished streamflow in two sub-basins. These results underscore the critical role of spatial configuration and landscape structure in modulating hydrological processes at the watershed scale. To better understand forest ecosystems role in water regulation, it is necessary to demonstrate how restoration efforts, conservation strategies, and increased forest patch aggregation contribute to the modulation of the water cycle at spatial scales. Spatiotemporal LUCC (Land Use and Cover Change) simulations are effective and reproducible tools for analyzing both the causes and consequences of alternative future landscape dynamics, in relation to socio-economic and natural environmental driving forces. The Future Land Use Simulation (FLUS) model enables the exploration of multiple LUCC scenarios by integrating human and environmental influences. The proposed modeling framework combines a top-down System Dynamics (SD) model with a bottom-up Cellular Automata (CA) model. The SD component projects land use demands based on diverse socio-economic and environmental drivers at national or regional scales (Liu, 2017). Using this model, it has been demonstrated that the expansion of urban and mining areas has significantly reduced ecological spaces, increased carbon emissions, and degraded habitat quality (Feng Y., 2025). Building on this foundation, an enhanced FLUS-3D model has simulated the future

evolution of urban dynamics in metropolitan regions under various Shared Socioeconomic Pathways (SSPs), further demonstrating its applicability in urban climate change mitigation studies and its potential contribution to achieving sustainable urban development (Xu, 2024). The PLUS model is built on meta cellular automata (CA) and is based on raster data. Patches are generated for land-use change simulation. As a nonlinear dynamic change simulation model with a fast run speed and high simulation accuracy, PLUS can easily describe land-use changes within specific time intervals (Xun Liang 2021). "Through this model, it has been possible to link land use development with ecological impacts in urban areas. The dynamics of land use and its potential for carbon storage and emissions in urban environments and its implication in the habitat quality and soil erosion (Yifeng Hou 2025, Aohui Wu 2025, Xinyan Zhao 2025, Jiaping Zhang 2025, Chao Tian 2025, Dongling Ma 2025). On the other hand, some authors have established the relationship between future LUCC scenarios and their impact on urban ecosystem services and the distribution of species such as glacial relicts, using artificial neural networks, regression models, and the MOLUSCE plugin in QGIS (Zarandian et al 2023, Sujit Kumar Roy et al 2024, Michael Boxriker 2025). Another approach to developing future land-use scenarios involves expert judgment. For example, Martínez et al. (2017) evaluated how key global change drivers climate change, urbanization, and fire regimes—might impact ecosystem services in Central Chile by 2050. Focusing on carbon storage, wine production, and scenic beauty, they created scenarios based on expert interviews, identifying climate change and urban expansion as the most influential factors. Similarly, Xinyan Zhao et al. (2025) used expert surveys to define levels of arable land restoration, assessing its potential to enhance grain production while minimizing losses in regulating ecosystem services. Raffaele Pelorosso et al. (2025) simulated two contrasting land-use futures: one involving the renaturalization of 600 hectares, and another characterized by 89 hectares of urban expansion. By integrating these scenarios with climate change projections, they analyzed the effects on bioenergy landscape connectivity. In the work of Rex Steward et al. (2025), land-use scenarios were developed through a four-step process that included expert judgment, interviews, and participatory workshops to simulate possible development trajectories. While land-use change (LUCC) models have been widely used to assess the interactions between future land-use trajectories and climate change, most of the existing literature has concentrated on urban expansion and its environmental consequences. However, there is a critical research gap concerning the hydrological implications of large-scale native forest restoration, particularly in terms of water supply ecosystem services.

Although such extensive restoration may not represent the most likely land-use trajectory, simulating these interventions could offer valuable insights into their potential to modulate water balance and broader hydrological functioning especially in areas that have not yet experienced intense urban development.

Chile presents a particularly relevant case for this type of research. First, the country has experienced significant land use and cover changes (LUCC), primarily driven by unsustainable land management practices (Aguayo et al., 2009; Echeverría et al., 2012; Heilmayr et al., 2016; Rodríguez-Echeverry et al., 2018). Second, southern-central Chile has been subjected to increasing water stress over the last decade, a situation projected to worsen with future climate scenarios predicting up to a 40% decrease in precipitation (Araya-Osses et al., 2020; Garreaud et al., 2020). Additionally, while past studies in Chile have modeled landscape change to assess the effects of forest conservation policy instruments often shaped by competing public planning and conservation coalitions, they have not explicitly examined whether these policies are sufficient to mitigate hydrological impacts under drier future conditions (Manushevich D. et al 2016; Henríquez-Dole et al. 2018). To address this knowledge gap, this study evaluates the hydrological effects of large-scale forest restoration and conservation scenarios. The research focuses on two sub-basins of the Imperial River in the Araucanía Region an area selected due to the availability of previously calibrated and validated hydrological data (Hernández et al., 2024), providing a solid technical foundation for simulation. Four restoration-conservation scenarios for native forests and forest plantations were developed based on 2017 land-use data, informed by Nature-Based Solutions (NBS), the Restoration Opportunities Assessment Methodology (ROAM), national environmental policies, and socio-environmental considerations. The main objective of this study is to determine whether forest restoration, despite projected reductions in precipitation can contribute to maintaining streamflow at the watershed outlet. This assessment is conducted using the TETIS hydrological model, which allows for a detailed simulation of land cover change impacts on water balance components. This approach also enables the comparison of restoration strategies involving native species versus exotic plantations in terms of their effectiveness for water-related ecosystem service provision and climate resilience.

2. Methodology

2.1. Study area

The Quino and Muco basins are located within the IX Region of Araucanía in southern Chile, situated at geographical coordinates of (38° 00' 00" S, 72° 20' 00" W - 71° 45' 00" W) according to the WGS84 datum. The rivers tribute to the Imperial River and have an area of 301 km² (Quino) and 649 km² (Muco). Its elevation varies between 200 to 1700 meters above sea level m.a.s.l (Fig 1). Mediterranean climate predominates, with mean rainfall around to 1900 mm per year, and mean air temperature approximately 10.0°C. Wet season extend from April to September, showing the lowest temperature, while dry period occurs from October to March, with the highest temperatures record. The mean annual streamflow ranges from 760 to 400 m³/s, with average daily discharges of 24 m³/s at the Longitudinal (Quino) station and 13 m³/s at the Puente Muco (Muco) station, respectively. As of 2017 land-covers for both basins were: crops (27%), native forest (26%), shrubland (17%), plantations (17%), grasslands and soils devoid of vegetation (11%), urban areas (0.34%), and water bodies (0.03%). The Quino basin exhibits a higher percentage of its territory being intervened (55%), while the Muco basin has (39%) (Hernández-Sosa et al., 2025). The native forest is dominated by *N. dombeyi*, *N. alpina*, *N. obliqua*, *D. diacanthoides*, *L. philippiana* (Esquivel et al., 2019). Meanwhile exotics plantation is dominated by *Pinus radiata* and *E. globulus* (Balocchi et al., 2020; Huber et al., 2010b).

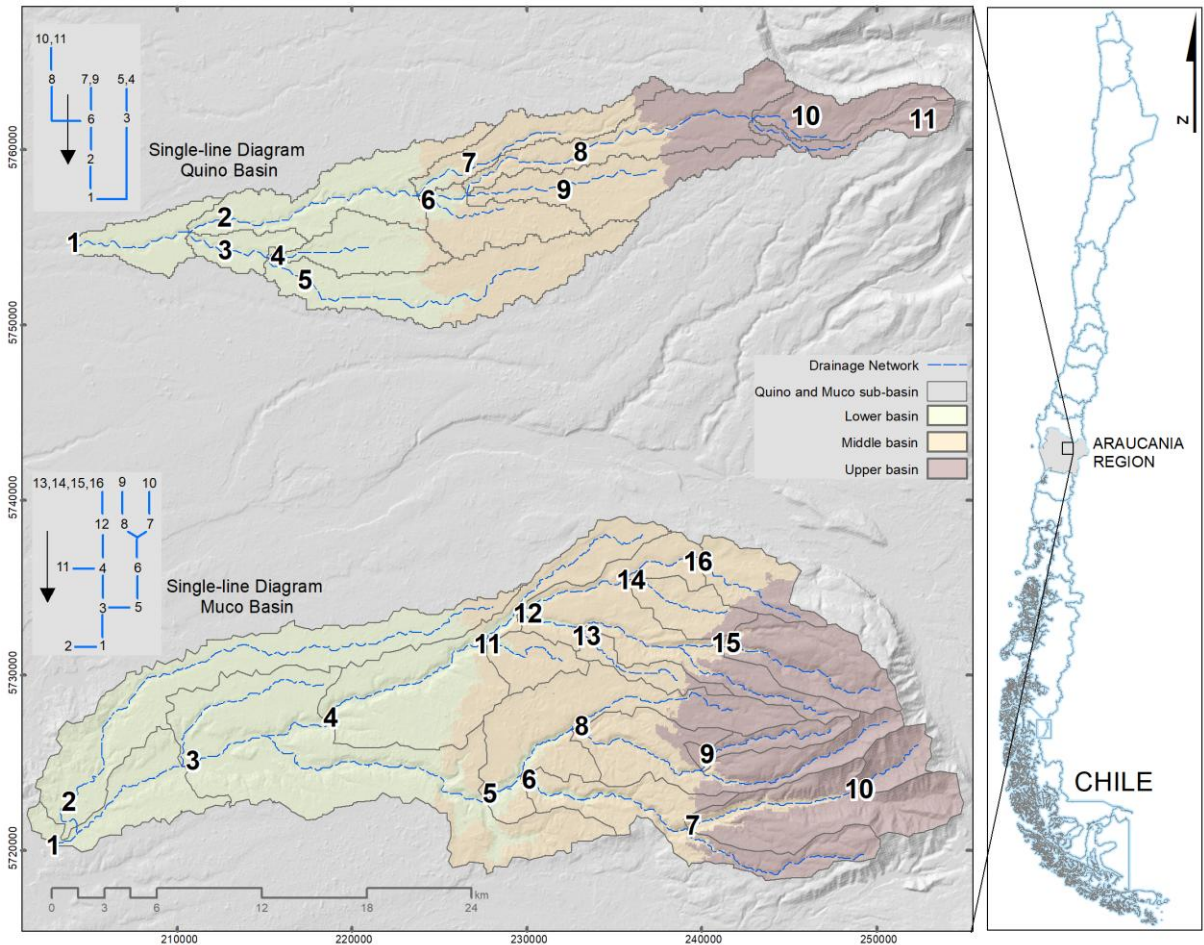


Fig 1 Location, single line diagram of sub-basin and watershed zones of Quino and Muco

2.2. Modeling land-used scenario.

Four future land use scenarios were developed based on the 2017 land cover classification for the Quino and Muco basins (Fig. 2). These scenarios were specifically designed to evaluate the potential benefits to components of the water cycle resulting from forest restoration, drawing from an extensive literature review (Table 1). The BN60M restoration scenario focuses on the rehabilitation of riparian zones, applying Nature-Based Solutions (NBS) and sciences publications associated with native forest restoration and conservation (IDs: ID1, ID2, ID5). The width of the riparian buffer zones was established in accordance with Chilean environmental regulations (IDs: ID10, ID11) and guided by NBS ID3, ID8, ID9. The BN50 and FR50 scenarios were constructed following the guidelines provided by IDs: ID4, ID5, ID7, and ID13. These scenarios promote large-scale landscape restoration in the mid-to-upper basin areas, driven by anticipated hydrological benefits, cultural heritage preservation for Indigenous Peoples, and a regionally prevalent social perception: "When forestry companies

leave, water returns." The BN50 scenario emphasizes restoration using native species, whereas the FR50 scenario implements restoration through forestry plantations. This framework aims to reduce uncertainty surrounding the hypothesis: Are forestry plantations more detrimental to the water cycle than native forests? The BN80 scenario proposes near-complete ecological restoration of the watershed, while excluding urban areas, water bodies, and grasslands. It adheres to the standards defined by IDs: ID4, ID5, ID7, and ID13. This scenario provides a benchmark for evaluating the hydrological impact of extensive native forest reconstruction. Agricultural land uses were preserved in the BN60M, BN50, and FR50 scenarios, consistent with regional economic development policies in the Araucanía region (ID12). Grassland areas were maintained across all scenarios due to their positive contribution to the water balance, as outlined in NBS ID6. The restoration and protection of both native forests and forestry plantations were addressed collectively, based on findings by (Hernández-Sosa et al., 2025). A fragmented native forest landscape alters flow and hydrological processes, whereas a forest plantation landscape with lower edge contrast tends to enhance hydrological functioning. The spatial configuration of the scenarios is illustrated in (Fig. 2). The percentage of restored areas of landscape scenarios relative to the 2017 land use conditions was: Quino Basin: 12% (BN60M), 40% (BN50/FR50), and 74% (BN80), Muco Basin: 6% (BN60M), 39% (BN50/FR50), and 62% (BN80). The classification of low, medium, and high elevation zones within both watersheds was performed by calculating the mean elevation from the digital elevation model (DEM) and adjusting it by ± 0.5 times the standard deviation of elevation values within each watershed (Fig 1).

Table 1. Land-use scenario development criteria.

ID	LAND USE	ASPECT	INTERVENTION	IMPLEMENTATION	BENEFIT	REFERENCE
1	Natural Forest	NBS	Restoration	Ecological restoration through native species reintroduction.	<i>Water Availability</i> Wildlife Corridors Erosion Control Carbon Sequestration	NBS. COP 25 CHILE. (Marquet & Rojas, 2021)
2	Natural Forest	NBS	Preservation	Prevention of native forest conversion.	<i>Water Availability</i> Wildlife Corridors Erosion Control Carbon Sequestration	NBS. COP 25 CHILE. (Marquet & Rojas, 2021)
3	Natural Forest	NBS	Reforestation	Riparian zones (30, 60, 200 m).	Carbon Sequestration. Water Quality and <i>Water Availability</i>	NBS CHILE (Marquet et al., 2021)
4	Natural Forest	NBS	Protection Restoration	Recovery of 350 million hectares with a focus on Indigenous and local community protection	<i>Water Availability</i>	COP27. THE SHARM-EL-SHEIKH ADAPTATION AGENDA. (Climate Champions, 2022)

5	Natural Forest	NBS	Restoration	Ecological restoration of natural forest ecosystems.	Water Resources and Soil Protection Enhancing cultural values	NATURE-BASED SOLUTIONS TO ADDRESS GLOBAL SOCIETAL CHALLENGES. (Cohen-Shacham et al., 2016)
6	Grassland	NBS	Preservation	Conservation of grassland ecosystems.	Water Availability	NBS. COP 25 CHILE (Marquet & Rojas, 2021).
7	Natural Forest	UICN	Reforestation	Landscape Approach (Large-Scale Restoration). The watershed with the highest level of restoration (50%)	Carbon Sequestration Water Availability	RESTORATION OPPORTUNITIES ASSESSMENT METHODOLOGY (ROAM). (UICN y WRI 2014)
8	Natural Forest	SCIENCIE	Reforestation	Riparian zones (60 m).	Nutrient removal, riparian zone	(T.R. AGUIAR.ET AL., 2015)
9	Natural Forest	SCIENCIE	Reforestation	Riparian zones (60 m).	Water-related ecosystem services Sediment retention Riparian vegetation	(FACHINELLI & JR, 2023)
10	Natural Forest	POLICY Art. 5 (1,2,3)	Preservation	Slope \geq 45%, Natural Forest within 200 m of watercourses.	Natural Forest	DECREE NO. 4363. MINISTRY OF LANDS AND COLONIZATION OF CHILE.
11	Natural Forest	LAW Art.2(5)	Preservation Protection	Slope \geq 45%, Natural Forest within 200 m of watercourses.	Water Resources Protection	FOREST REGULATIONS (CONAF) LAW NO. 20.283 ON THE RECOVERY OF NATIVE FOREST AND FOREST PROMOTION. (2008).
12	Crops	Economics Factor	Agricultural and Tourism	Tourism: East (High-mid zone) Crop: West (mid-low zone)	Socioeconomic	ARAUCANIA IMPULSE PLAN: CONTRIBUTING TO RECONCILIATION AND THE DEVELOPMENT OF OPPORTUNITIES. (2019)
13	Natural Forest	Social Factor	Local Reflective Perspective	Restoration and Eradication of Forest Plantation Ecosystems	Without forests plantation, They have water.	PRIORITY AREAS FOR NATIVE FOREST RESTORATION. WATER PROVISION IN FORESTED WATERSHEDS. (Little et al., 2015.)

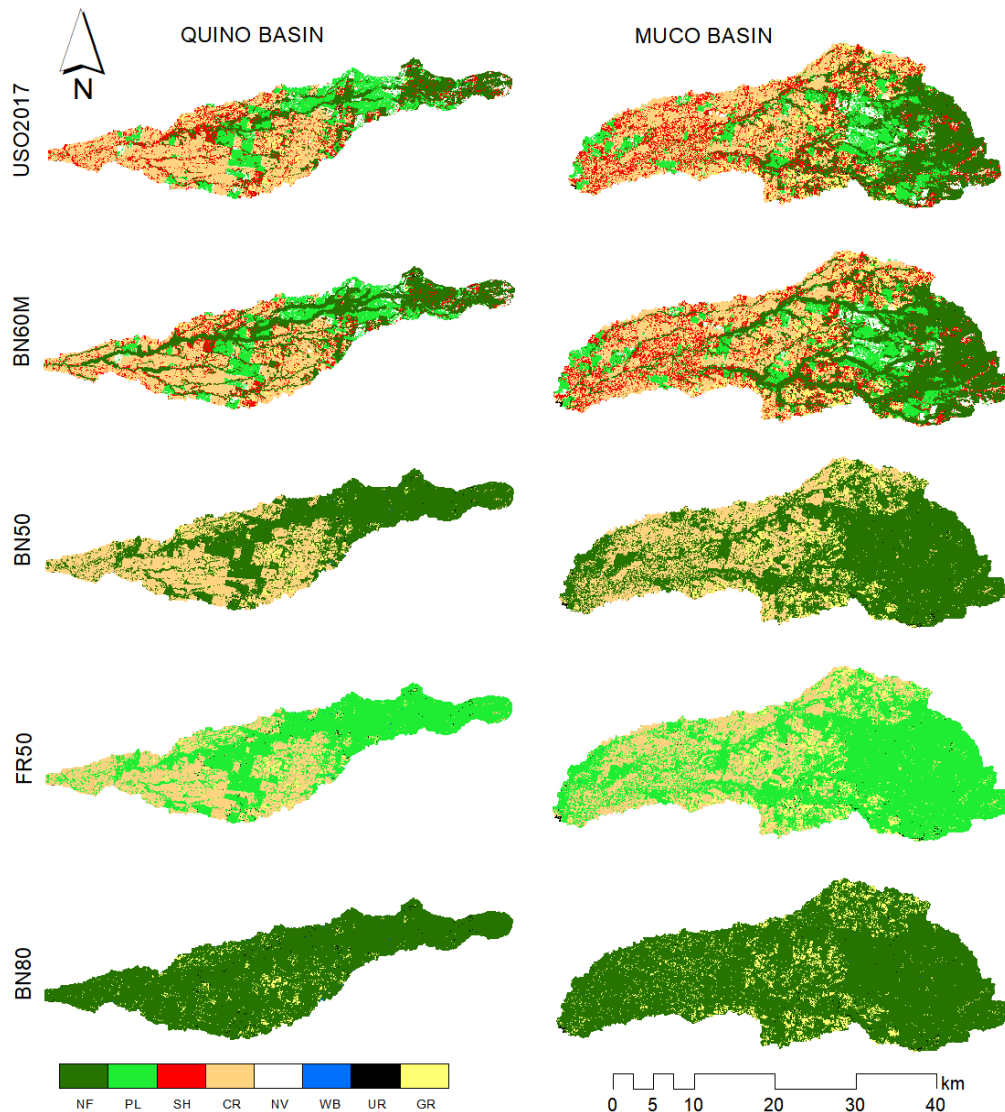


Fig 2 Restoration - conservation scenarios for Quino and Muco basin. Native Forest (NF), Plantation (PL), Shrubland (SH); Crops (CR), Not Vegetation (NV), Water Bodies (WB), Urban (UR), Grassland (GR)

2.3. Hydro-meteorological data.

Daily data on mean temperature and precipitation were used from three datasets: observed records (1975 - 2005), historical simulations (1975 - 2005), and two future time projections intervals middle future (2030 - 2060) and far future (2061 - 2091), obtained from the Climate Science and Resilience Research Center (CR2) repository www.cr2.cl, for 30-year. The historical period 1975–2005 was selected due to the greater availability and continuity of meteorological data in the Araucanía Region. Quillen station $38^{\circ} 27' 36''$ S, $72^{\circ} 23' 24''$ W, were representative for precipitation and temperature data. Future climate projections

correspond to models from the CORDEX-South America regional ensemble (SAM20, SAM22, and SAM44i) under the Representative Concentration Pathway RCP8.5. Taylor diagrams were used to assess model performance (Taylor, 2001). In the case of precipitation, the CanESM2 model demonstrated the best agreement with the observed data in terms of correlation and standard deviation. Conversely, for mean temperature, RegCM4 model stood out for having the highest correlation and a standard deviation closest to the observed data (Fig. 3).

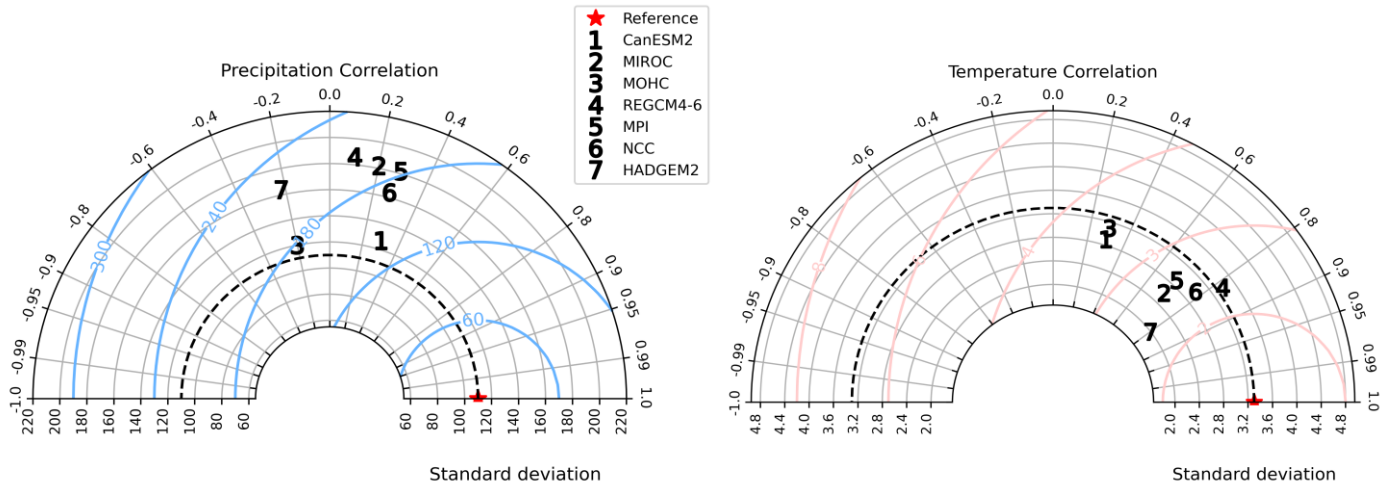


Fig 3 Taylor Diagram: Comparison of historical simulations (CORDEX) and observed data. Precipitation and mean temperature. Period 1975–2005.

2.4. Hydrological modeling.

The results of the impact on the components of the water cycle from the combination of climate change and land use scenarios were obtained using the TETIS hydrological model. This model is a spatially distributed conceptual hydrological model with physically based parameters (Francés et al., 2007b). The parameters required for the proper functioning of the model, are described below. Land use maps were obtained from the classification by (Heilmayr et al., 2016b) with a 30-meter resolution. Soil information (i.e., texture, soil depth, organic matter content, and permeability) was extracted from the Agrological Studies of the VIII Region based on data from the Center for Natural Resources Information (CIREN) and SERNAGEOMIN (2002). Lithological data were obtained from the National Catalog of Geological and Mining Information of Chile at a scale of 1:1,000,000 (SERNAGEOMIN, 2004). The digital terrain model (DTM) was extracted from ALOS-1 PALSAR images with a spatial resolution of 30 meters (<http://vertex.daac.asf.alaska.edu>, accessed January 23, 2023).

Parameters such as flow direction and accumulation, slope velocity, and slope were derived from DTM. Static storage in the upper soil layer (HU) was calculated as the sum of surface storage and available water content, the latter being estimated by multiplying root depth by the available water capacity of the soil. Surface storage was estimated using land cover and slope maps, following the methodologies outlined by (Francés et al., 2007b). Infiltration capacity (KS) and percolation capacity (KP) were obtained from (Tyagi et al. 2022). Deep aquifer loss capacity (KPs) was determined based on the lithological characteristics of the basin's geological formations. For saturated horizontal hydraulic conductivity (Ksa) and deep aquifer flow velocity (Kps), the following assumptions were applied: $Ksa = Kp$ and $Kps = 0.1 \times Kp$ (Gomis-Cebolla et al., 2022b). The calibration and validation results of the TETIS model in the Quino and Muco basins can be consulted in the study by (Hernández-Sosa et al., 2025). In this study to determine the differences between forest plantations and native forests using the TETIS model, four parameters were specific regulated based on the vegetation cover present in each land use scenario: root depth, monthly vegetation factor (λ_v), interception, and the spatial distribution of HU. The selected values were adjusted using data from (Allen et al., 1998; Balocchi et al., 2020; Meléndez D. 2014; Huber et al., 2010; Liu et al., 2017), and expert judgment.

2.5. Statistical analysis.

To assess the magnitude of change in simulated precipitation between the future periods (2030 - 2060) and (2061 - 2091) relative to the reference period (1975 - 2005), a comparative analysis was conducted using seasonally averaged precipitation. This analysis was based on the Standardized Precipitation Index (SPI), developed by (McKee et al., 1993). The SPI it has been widely adopted in international research (Cheval, 2015; Long et al., 2024; Zelenáková et al., 2023). Two comparative analyses of the number of rainy days relative to the baseline period were also conducted. These were based on: (i) an increase or decrease in daily rainfall of 0.5 mm, and (ii) variations in the 75th percentile values for both wet and dry seasons. Extreme temperatures were assessed using standardized anomalies of seasonal mean temperatures, and thermal amplitude was analyzed to evaluate whether rising mean temperatures are driven more by minimum temperatures or both extremes. Implications for reference evapotranspiration were also considered, with estimates based on the Hargreaves equation (Hargreaves et al., 1985). A violin plot was generated to show Actual Evapotranspiration (AET) change over forested areas under different land-use scenarios,

based on daily outputs from the TETIS model. Data were aggregated annually, and pixel-level values were extracted from the Quino and Muco sub-basins using a Phytom-based script. The plot displays evapotranspiration differences between the 2017 baseline and future scenarios (BN60M, BN50, BN80, FR50). For the baseline and BN60M, mean AET was averaged across forest plantations and native forests due to their co-occurrence, unlike in the other scenarios with homogeneous forest cover. AET, ($\Delta AET_{\text{period}}$) was calculated using a standard equation.

$$AET_{\text{period}} = AET_{\text{Reference Sub-basin, period}} - AET_{\text{Scenario Sub-basin, period}} \quad (1)$$

Where: $\Delta AET_{\text{period}}$ is the change in reference evapotranspiration for a given time period. $AET_{\text{Reference Sub-basin, period}}$ is the AET value for the reference land use under a climate scenario. $AET_{\text{Scenario Sub-basin, period}}$ is the AET value under a projected land use for the same period. The analysis of streamflows from the baseline LUCC 2017 scenario and the four restoration scenarios under the climate forcing was carried out using three approaches: percentage change, flow duration curves (exceedance probability), and a Hydrological Performance Forest Index (HPFI), developed by the authors. Most of these analyses were conducted by wet and dry seasonal periods, and for normal, wet, and dry years. The flow duration graphs represent the average streamflows of sub-basins with restored areas of ≤ 15 and > 15 km² for the Quino River, and ≤ 20 and > 20 km² for the Muco River. These thresholds (15 and 20 km²) were selected based on the average restored area assigned to each sub-basin. The HPFI was developed to establish a dimensionless metric that accounts for sub-basin size and forested area and allows comparison between expected streamflow under the 2017 baseline scenario and the flows generated under land use change scenarios influenced by climate change forcing. The area of the sub-basin, as well as the discharge, considers the flows and areas of the contributing tributary basins in each case from the stream network diagram (Fig 1).

$$HPFI = \frac{AREAf_{\text{sub}}}{AREAt_{\text{sub}}} \times \frac{Qf_{\text{sub}}}{Q_{\text{sub}}}$$

(2)

Where HPF is a dimensionless metric that quantifies the effectiveness of forest cover in influencing streamflow relative to a baseline year, based on data simulated through hydrological modeling, which already accounts for other physical and geographical variables. AREAf represents the forested area within the sub-basin, corresponding to the land surface that has been afforested or reforested in the modeled scenario. AREAt denotes the total area

of the sub-basin, encompassing the entire watershed or catchment under evaluation. Q_f is the streamflow under forested conditions, defined as the simulated river discharge for a scenario and Q_{sub} refers to the reference streamflow, in our study the 2017 land use. As a final step, the water balance was calculated at the outlet of both watersheds Puente Muco and Longitudinal using the equation proposed by Sokolov and Chapman (1974). The water balance equation, applicable to any region or natural watershed (such as a river basin), represents the relative values of inflows and outflows, as well as the variation in water storage within the area or water body. The simplified form of the equation, resulting from the omission of certain terms due to the size of the watershed, the definition of the watershed divide, and the seasonal periods analyzed, is presented below.

$$P - E - Q - \Delta S = 0 \quad (3)$$

In the water balance equation, P is precipitation, E is surface evapotranspiration, Q is river discharge, and ΔS represents changes in water storage. When inflows exceed outflows, storage increases, and vice versa. All values were derived from the TETIS hydrological model for the years 2044–2046 and 2070–2072, chosen to represent normal, above-normal, and below-normal precipitation based on P25 and P75 percentiles (Fig 4).

3. Results

3.1. Land use change scenarios

According to Hernández et al. (2024), the Quino and Muco watersheds have experienced significant land use changes since the 1980s, primarily due to agricultural expansion and the establishment of forest plantations starting in the early 2000s. Native forests, along with shrublands and grasslands, have been the most affected, with current native forest cover reduced by half compared to 1986, particularly in the Quino basin. On the other hand, this region has not experienced significant urban development, as confirmed by the land use reclassification conducted by Heilmayr et al. (2016) for the periods 1986, 2001, and 2011. Table 2 summarizes land use areas (km²) for 2017 (baseline scenario) and other projected scenarios. In 2017, agricultural land was the predominant land use, followed by native forests, shrublands, grasslands, and smaller areas of urban zones, barren land, and water bodies. Under various restoration scenarios (BN60M, BN50, FR50, and BN80), driven by policies such as Law 20.283 and Decree 4363, both native forests and forest plantations show a significant

increase in coverage, particularly along riparian zones and the mid-to-upper sections of the watersheds, while agricultural land remains in the lower areas. The BN80 scenario emphasizes conservation, restoring nearly the entire territory with native forests, although it is considered the least likely outcome based on historical land-use trends. (Heilmayr et al., 2016; Hernández et al., 2024).

Table 2. Land use and land cover distribution by scenario (km²).

Land Used Scenarios	Native Forest	Plantation	Agriculture	Shrubland	Grassland	Water	No vegetation	Urban
2017	240.0	152.1	254.1	160.1	71.0	0.4	35.2	3.2
Bn60	312.1	133.5	234.7	134.1	66.7	0.4	31.4	3.2
BN50	586.1	0.0	255.4	0.0	71.0	0.4	0.0	3.2
BN80	841.4	0.0	0.0	0.0	71.0	0.4	0.0	3.2
FR50	0.0	586.1	255.4	0.0	71.0	0.4	0.0	3.2

*2017: Current land use.

Bn60: Restoration of the riparian zone (60 meters).

Bn50: Restoration of more than 50% of the basin with native forest.

FR50: Restoration of more than 50% of the basin with forest plantations.

BN80: Restoration of more than 80% of the basin with native forest

Tables 3-4 present the native forest surface distribution for each land use scenario in the Quino and Muco watersheds at the sub-basin level. In Quino, sub-basins 2, 5, 8, and 9 show the largest average native forest areas across all scenarios, mainly located in the central-upper part of the watershed. Sub-basin 3, located in the lower watershed, shows the least restoration. Individually, sub-basin 8 has the highest reforested area across all scenarios. In Muco, sub-basins 3, 7, and 9 show the highest average restoration, with sub-basins 7 and 9 located in the upper watershed and sub-basin 3 in the lower part. Sub-basins 1 and 13 show the least change on average, with sub-basin 1 located downstream and sub-basin 13 upstream. Individually, sub-basin 9 shows the greatest intervention under the BN60M, BN50, and FR50 scenarios, while under the BN80 scenario, sub-basin 3 has the largest native forest area.

Table 3. Forest surface (Km²) in Quino sub-basin

Land Used Scenarios	Quino sub-basin.											Total Surface
	1	2	3	4	5	6	7	8	9	10	11	
2017	0.1	4.4	0	0.9	4.8	3.0	4.0	14.5	7.3	13.4	7.5	60.5
BN60	3.2	12	1.6	3.6	10.0	5.5	7.3	21.4	10.9	14.2	8.3	98.3
BN50/FR50	4.1	21.5	2.1	6.2	20.1	11.5	18.0	39.7	22.3	18.3	12.4	176.6
BN80	17.1	38.2	10.1	20.8	51.2	20.0	21.9	40.9	31.9	18.5	12.7	283.9

Average 6.1 19.0 3.5 7.9 21.5 5.5 12.8 20.1 18.1 16.1 10.2 154.8

Table 4. Forest surface (Km2) in Muco sub-basin

Land Used Scenarios	Muco sub-basin.																Total Surface
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
2017	1.7	0.5	11.4	8.0	14.6	21.1	23.3	6.7	29.3	10.0	2.2	20.4	3.0	4.0	25.5	6.1	187.9
BN60	5.7	1.8	19.0	14.0	17.8	24.0	26.1	7.5	31.2	10.3	2.4	24.8	3.0	4.0	26.5	7.1	225.1
BN50/FR50	12.9	36.0	55.9	30.8	40.2	34.2	43.7	10.4	44.8	11.5	12.7	41.8	9.6	10.0	31.8	11.2	437.5
BN80	6.6	70.0	100.0	61.0	50.6	36.5	45.0	10.5	45.4	11.0	10.6	50.3	9.0	12.5	32.0	16.0	587.0
Average	6.7	27.1	46.6	28.5	30.8	29.0	34.5	8.8	37.7	10.7	7.0	34.3	6.2	7.6	29.0	10.1	359.4

*The modified area is identical in all sub-basins for Scenario BN50/FR50. The forest surface in BN50 is (Native Forest) and FR50 (Forest Plantations).

3.2. Climatological analysis.

The behavior of the mean annual precipitation for both watersheds show the normal values within the gray band and the trend line for the 2030 - 2091 series. Precipitation exhibits a decreasing trend, particularly during the first period (2030 - 2060). At the beginning of the series, normal values are predominant; however, from 2060 onwards, below-normal values become more frequent. The right section of the figure shows the variation in streamflow relative to the reference period 1975–2005. A significant decrease in streamflow is observed across the different future scenarios, with reductions reaching up to 400 m³/s throughout much of the projected period. The figure is accompanied by the behavior of the Standardized Precipitation Index (SPI) for both wet and dry months, along with a trend line for every 10-year period. Although the precipitation index remains negative throughout the entire series indicating that dry years are expected according to the selected model. No marked reduction in precipitation is observed during the wet months, in contrast, a decreasing trend in precipitation is evident during the dry months, particularly intensifying between 2060 and 2080. Additionally, the behavior of the number of rainy days and dry days relative to the normal period (1975 - 2005) was analyzed. According to WMO, the precipitation of liquid water droplets with a diameter greater than 0.5 mm. The graph on the left shows that the number of rainy days tends to increase, especially between 2030 and 2060, primarily during the months of July, August, and September. In contrast, the number of dry days remains close to normal, with a slight increase observed during the 2061 - 2091 period. On the right-hand side, the analysis focuses on rainy days with precipitation values equal to or greater than the

75th percentile (P75) during both wet and dry months. The figure indicates a significant decrease in the number of wet days across both periods, while dry days show a more pronounced increase. These findings suggest that although the total number of rainy days remains relatively constant, drought events will primarily result from a reduction in daily precipitation totals, particularly those at or above normal values (Fig. 4). Standardized anomalies of mean extreme temperatures show an upward trend, ranging from 1 to 4 °C. Wet months exhibit decadal variability alternating between stable and rising temperatures while dry months (2030-2060) show a marked increase, followed by stabilization (2061-2091). Thermal amplitude decreases in both periods compared to the 1975-2005 baseline, especially early in the dry season, due to rising minimum temperatures while maximums remain stable. This shift leads to reduced future reference evapotranspiration, particularly during dry months, as estimated by the Hargreaves equation (Fig. 5).

3.3. Percentage Change in Drivers of the Water Cycle: Climate Change and Land Use Cover Change

Fig. 6 illustrates percentage changes in hydrological components for the Quino and Muco catchments. Climate change (CC) alone has the strongest impact (~30% increases in evapotranspiration and streamflow), showing high system sensitivity. LUCC-only effects are milder (~10%). Combined CC+LUCC scenarios show non-linear responses, with similar overall changes to CC alone but differences in specific variables CC+BN50 yields higher runoff and baseflow.



Fig 4 Mean annual precipitation (mm). Annual percentage change in streamflow (%). SPI for wet and dry seasonal. Wet (WD) and dry days (DD) monthly average (mm). Quino and Muco basin. Periods: 1975-2005, 2030-2060, 2061-2091

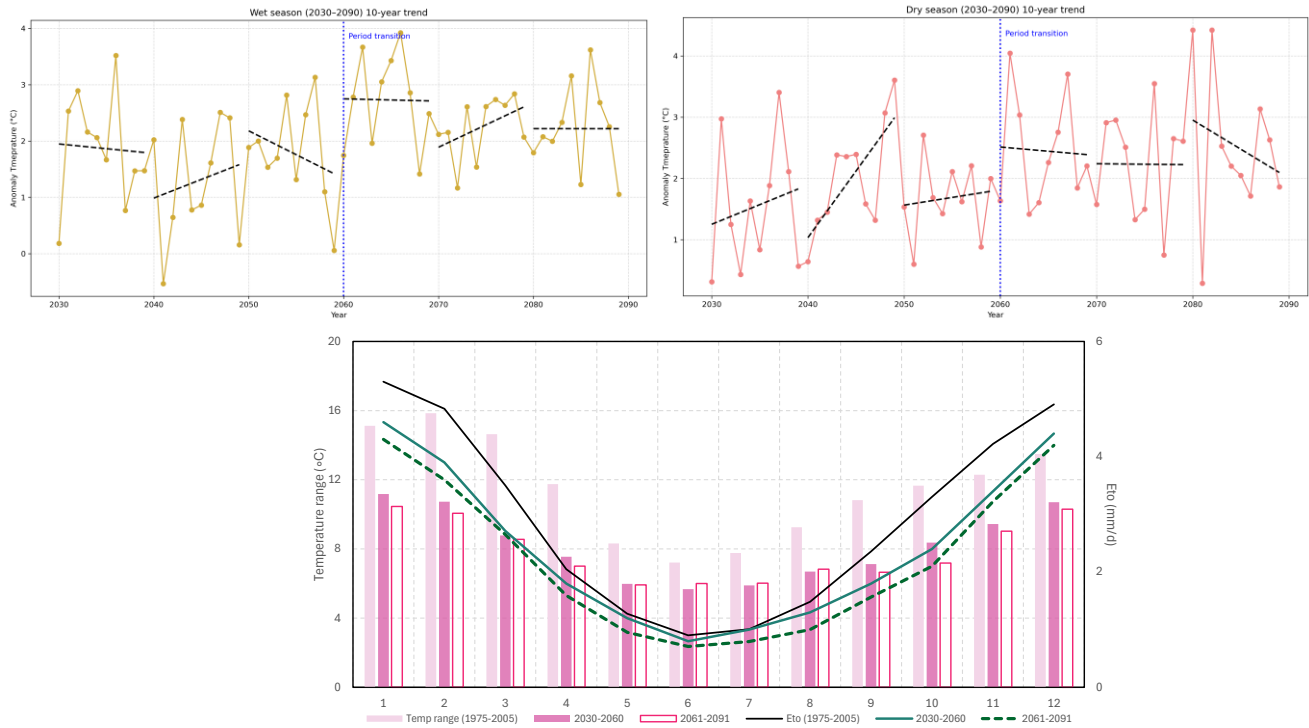


Fig 5 Anomaly for wet and dry seasonal (°C). Temperature range (°C) and Eto (mm/d) monthly average. Quino and Muco basin. Quino and Muco basin. Periods: 1975-2005, 2030-2060, 2061-2091

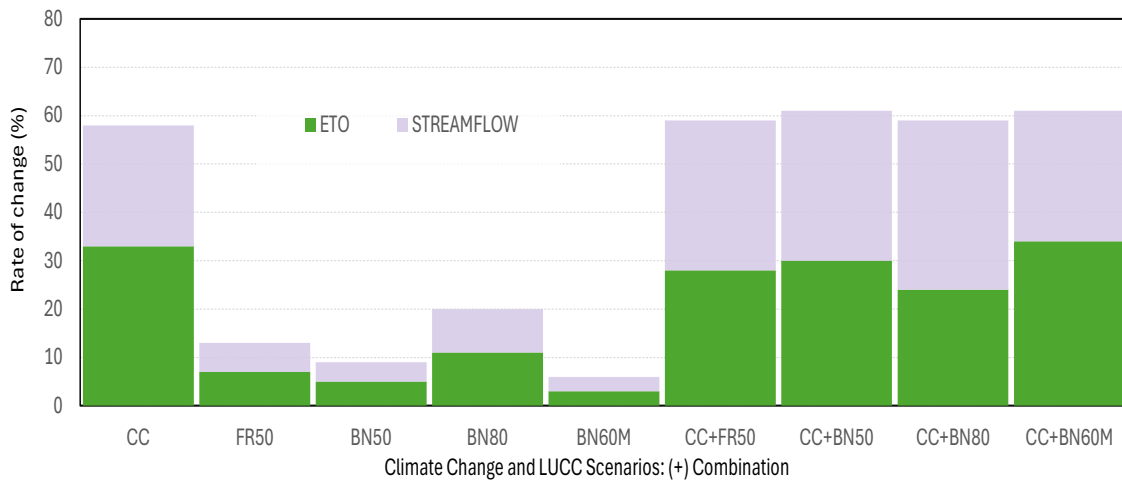
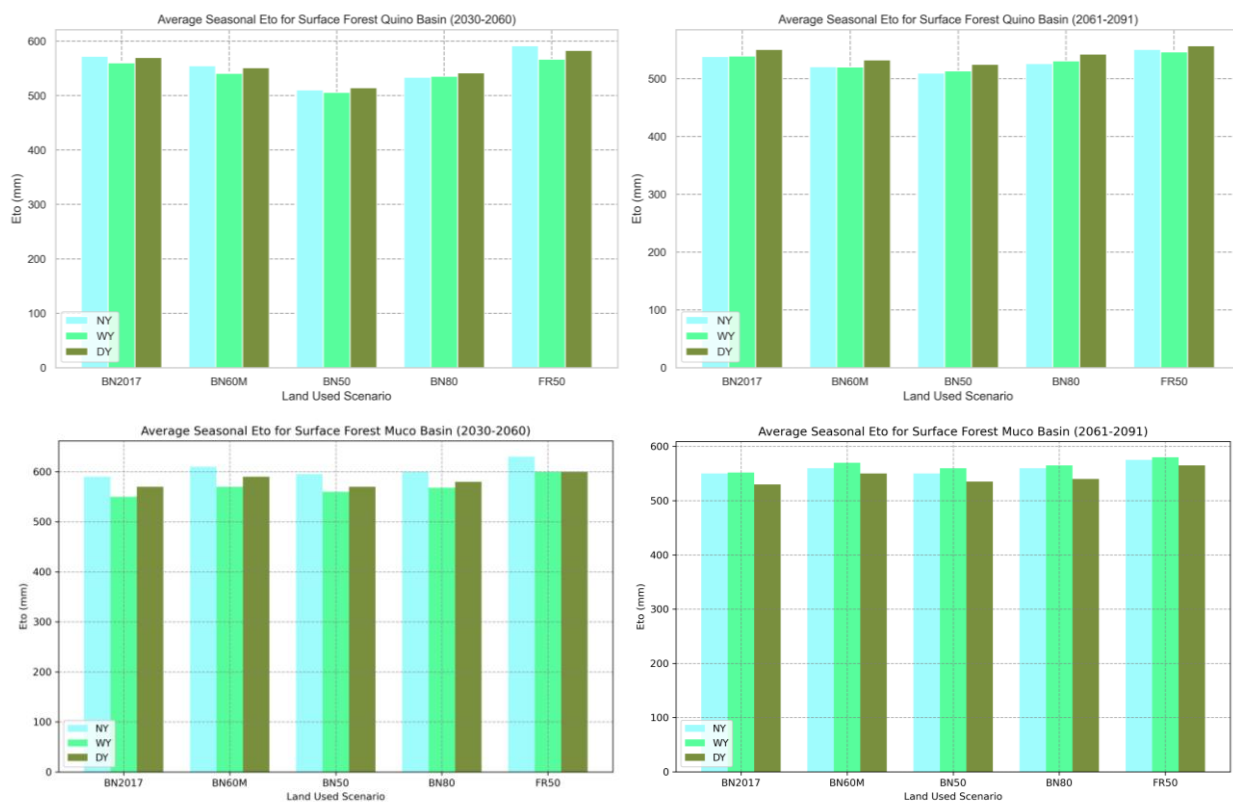


Fig. 6 Percentage Change in Drivers of the Water Cycle: Climate Change and Land Use Cover Change. Quino and Muco

3.4. Impact of Land Use and Climate Change Scenarios on Forest Evapotranspiration.

An analysis conducted for wet, dry, and normal years across both time series and for each land-use scenario reveals that PET is substantially higher under the scenario where forest cover is solely composed of forest plantations (FR50). In both watersheds, the scenario presenting slightly lower evapotranspiration values compared to the others is the BN50

scenario, particularly in the Quino watershed. In the Quino watershed, dry years exhibit the highest evapotranspiration rates, whereas in the Muco watershed, normal and wet years show the greatest evapotranspiration levels (Fig. 7A). The average annual behavior of total forest evapotranspiration (AET) across all scenarios, considering interannual variability, shows that the highest coefficient of variation (CV), at 9.6%, is observed in the forested scenario, which also records the highest AET values. Although differences between scenarios are minimal, a slight decrease in AET is observed in the current scenario compared to the reforestation scenarios with higher vegetation cover (Fig. 7B).



* The forest surface in BN2017-BN60M (Average Native Forest and Plantations), BN50 (Native Forest), FR50 (Forest Plantations) and BN80 (Native Forest).

Fig. 7A Annual AET and interannual variability (mm). Seasonal average forest surface evapotranspiration scenarios for Natural Year (NY), Wet Year (WY), Dry Year (DY). Quino and Muco basin. Periods: 2030-2060, 2061-2091

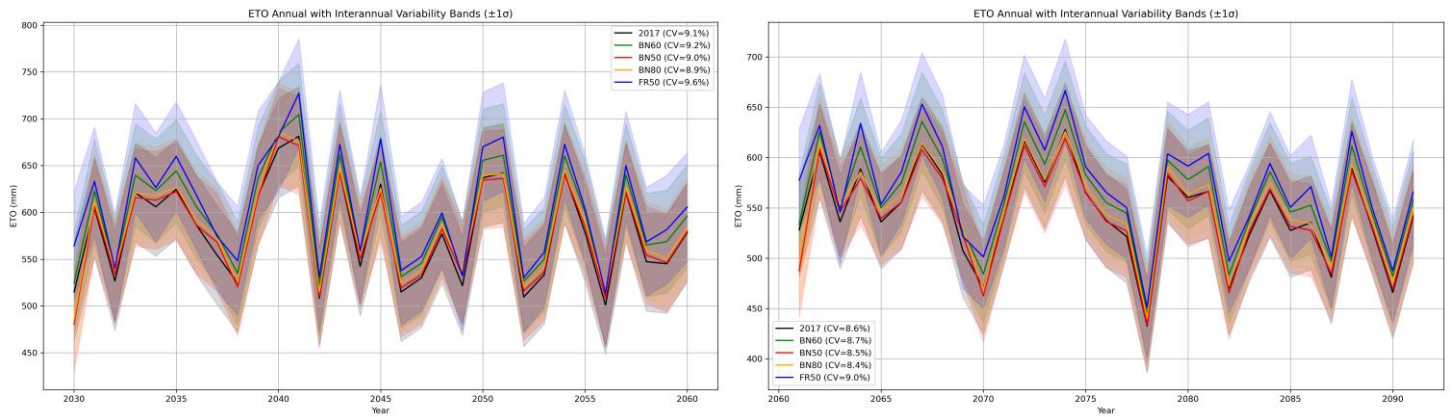


Fig. 7B Annual AET and interannual variability (mm). Seasonal average forest surface evapotranspiration scenarios for Natural Year (NY), Wet Year (WY), Dry Year (DY). Quino and Muco basin. Periods: 2030-2060, 2061-2091

The violin plots illustrate the distribution and probability density of differences in AET forest surface between the 2017 baseline scenario and a set of simulated land-use scenarios (BN60M, BN50, BN80, FR50) for the periods 2030 - 2060 and 2061- 2091, across the Quino and Muco sub-basins. Negative values indicate higher PET under baseline conditions relative to the simulated scenarios, whereas positive values denote increased AET under forested land cover. Across all scenarios, results consistently show that reforestation whether through native forest restoration or commercial plantations leads to enhanced water loss via evapotranspiration compared to the baseline, with the effect being particularly pronounced in the Muco basin. Among the scenarios analyzed, the riparian restoration scenario (BN60M) exhibits the smallest deviation from baseline AET levels. In contrast, the plantation forestry scenario produces the largest differences, characterized by relatively narrow violins indicative of lower variability across simulations and increases in evapotranspiration ranging from 20 to 40 mm, especially during the 2030 - 2060 period. The native forest restoration scenario, applied predominantly in areas currently covered by plantations and shrublands comprising nearly 70% of both basins, especially in mid-to-upper elevations results in notable reductions in AET, typically between 20 and 50 mm. These reductions are particularly evident in sub-basins located at higher altitudes. The associated violin plots are more symmetrical and narrower, suggesting lower inter-simulation variability when compared to the baseline scenario (Fig. 8).

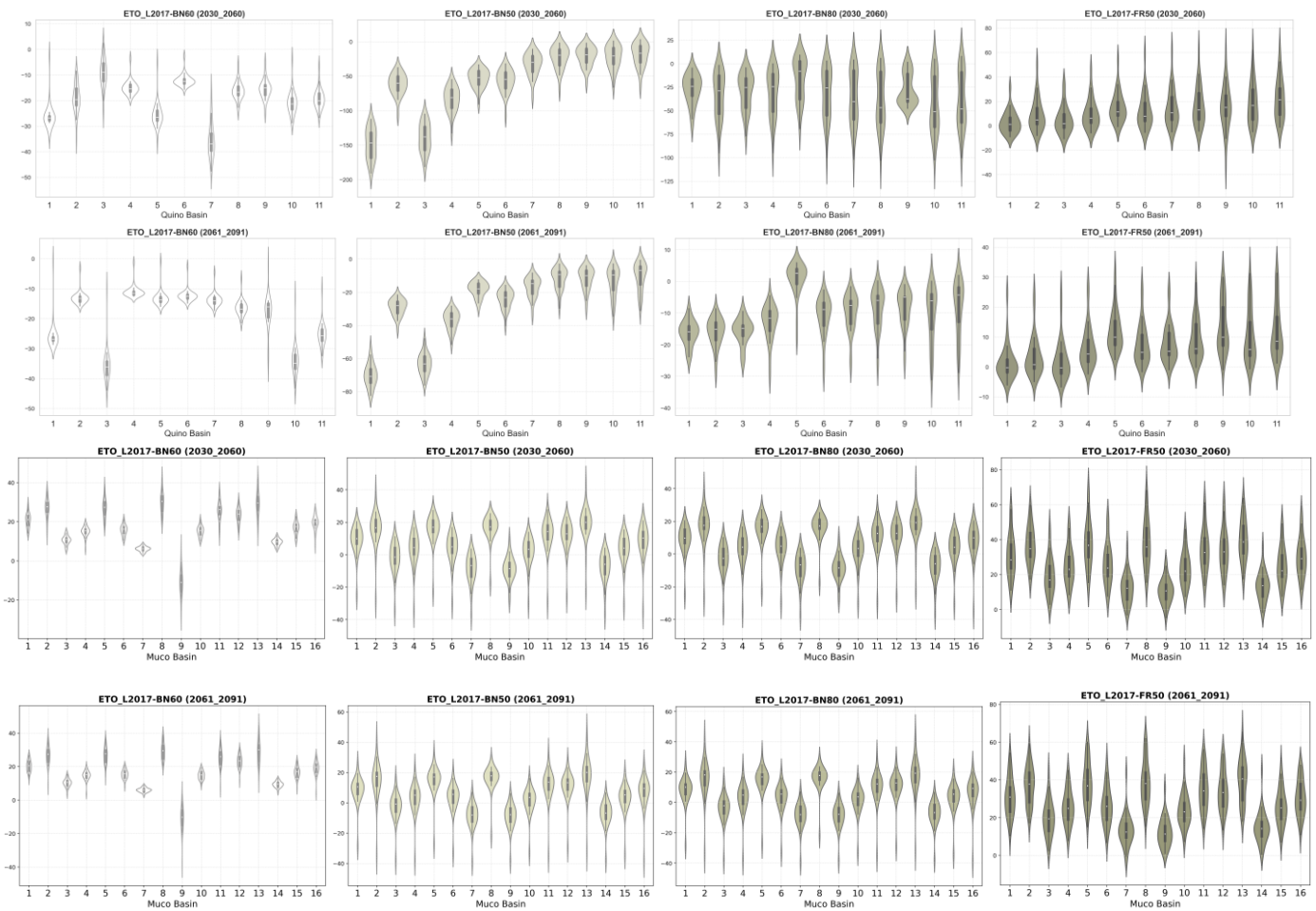


Fig 8 Violin plots of the differences in forest evapotranspiration (mm) between the 2017 baseline scenario and the restoration scenarios. Quino and Muco sub-basin. Periods: 2030-2060, 2061-2091

3.5. Effects of Land Use Change and Climate Change Scenarios Reforestation on streamflow

An analysis of streamflow contribution under different land-use scenarios, in the Quino and Muco sub-basin. While streamflow was generally similar across scenarios during the wet season, differences emerged during transitional and dry periods. In May–June, BN50 produced the highest streamflows in Quino, while the baseline did so in Muco. During the dry season (November - January), marking the transition from wet to dry months, the Muco basin shows higher streamflow percentages under the BN50 scenario. In the Quino basin, especially for the 2030 - 2060 period, the riparian restoration scenario followed by BN50 accounts for the highest relative contribution to total streamflow. In the second quarter of the dry season, both basins exhibit more pronounced differences at the sub-basin scale. For the 2030 - 2060 period, the sub-basins contributing the highest streamflow’s under the BN50 scenario are

located primarily in the mid-to-upper regions of both basins. For the 2061 - 2091 period, the scenario yielding the highest flows is the baseline, followed by BN50 (Fig. 9).

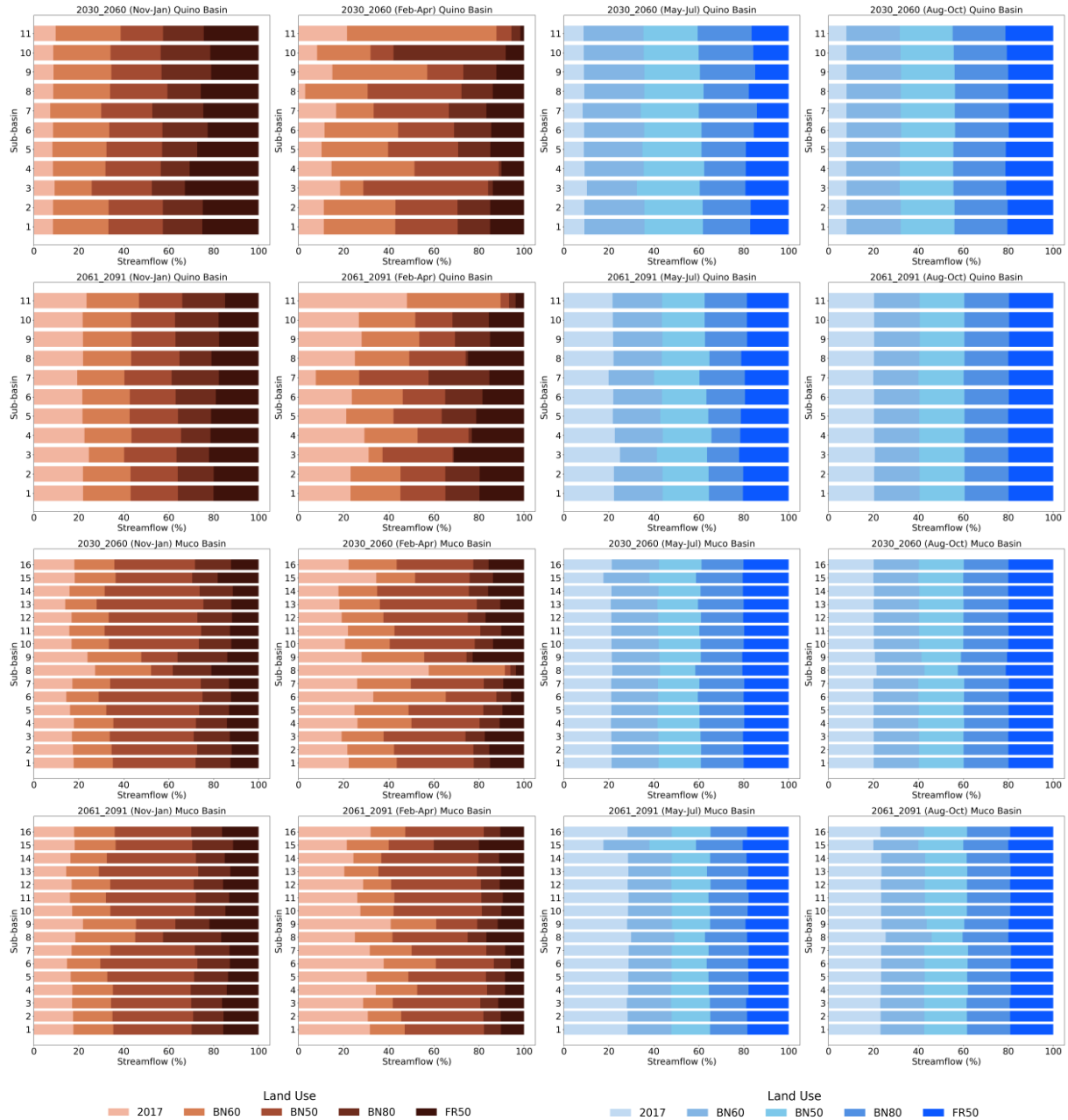


Fig 9 Percentage (%) of total streamflows from land use scenarios by quarter. Quino and Muco sub-basin. Periods: 2030-2060, 2061-2091

A probability of exceedance analysis was conducted to evaluate streamflow distributions in sub-basins with forested areas $\leq 15 \text{ km}^2$ and $> 15 \text{ km}^2$ (Quino), and $\leq 20 \text{ km}^2$ and $> 20 \text{ km}^2$ (Muco), under all land-use scenarios. Normal, wet, and dry years were considered. Results show that in sub-basins with smaller forested areas, the highest streamflows occur under the baseline (2017) and riparian restoration (BN60) scenarios, while forestation scenarios (FR50,

BN50) yield lower flows, highlighting the hydrological impact of increased forest cover. In larger forested sub-basins, BN80 produces the highest flows during extreme events. From a 0.4 exceedance probability onward, particularly in Quino, flow values across restoration scenarios converge, indicating reduced variability during more frequent, lower-magnitude events (Fig. 10-11).

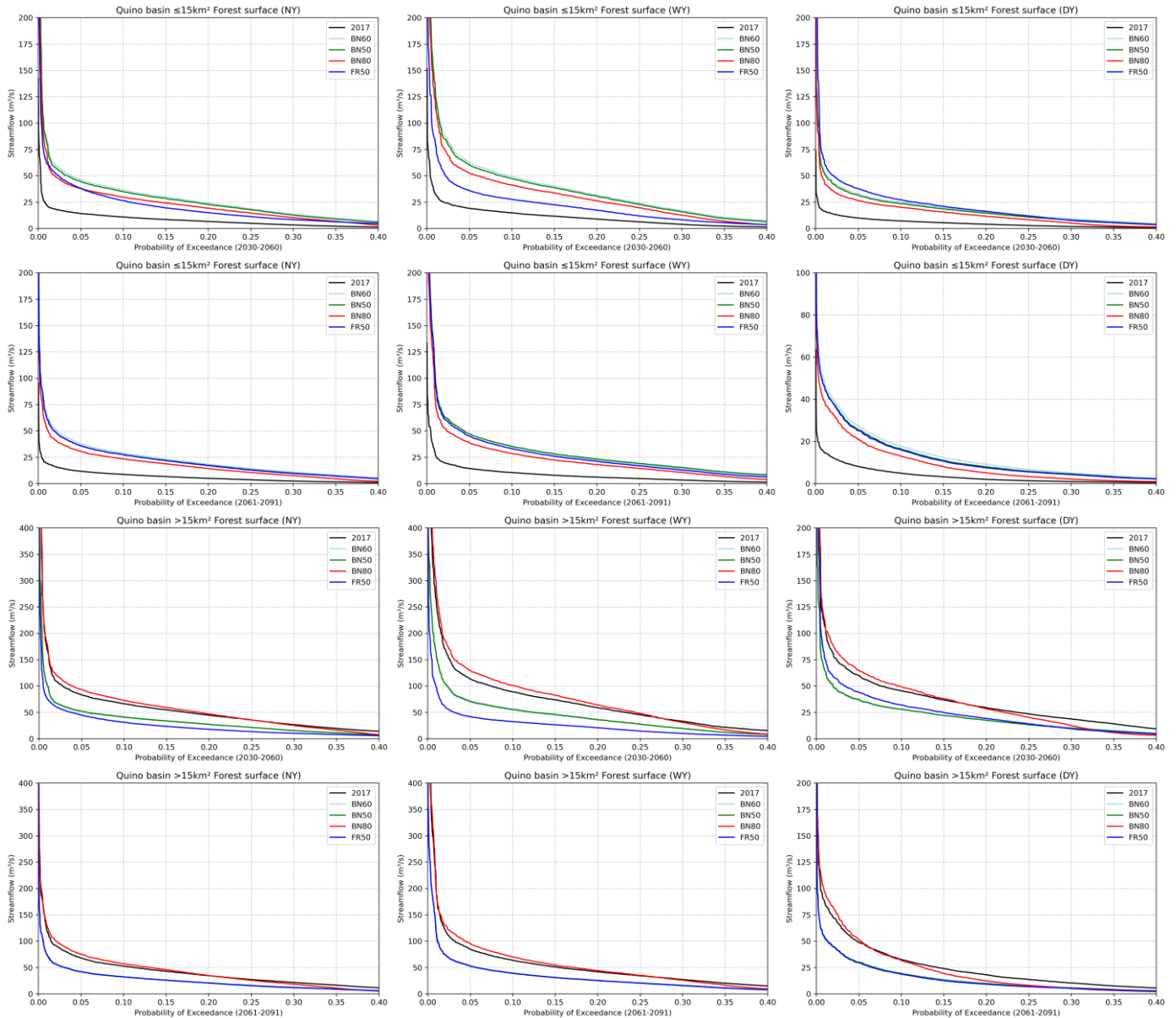


Fig 10 Probability of exceedance (m^3/s) of seasonal streamflow average for basin with forest surface ($\leq 15 \text{ km}^2$ and $> 15 \text{ km}^2$). Natural Year (NY), Wet Year (WY), Dry Year (DY). Quino sub-basin. Period: 2030-2060, 2061-2091

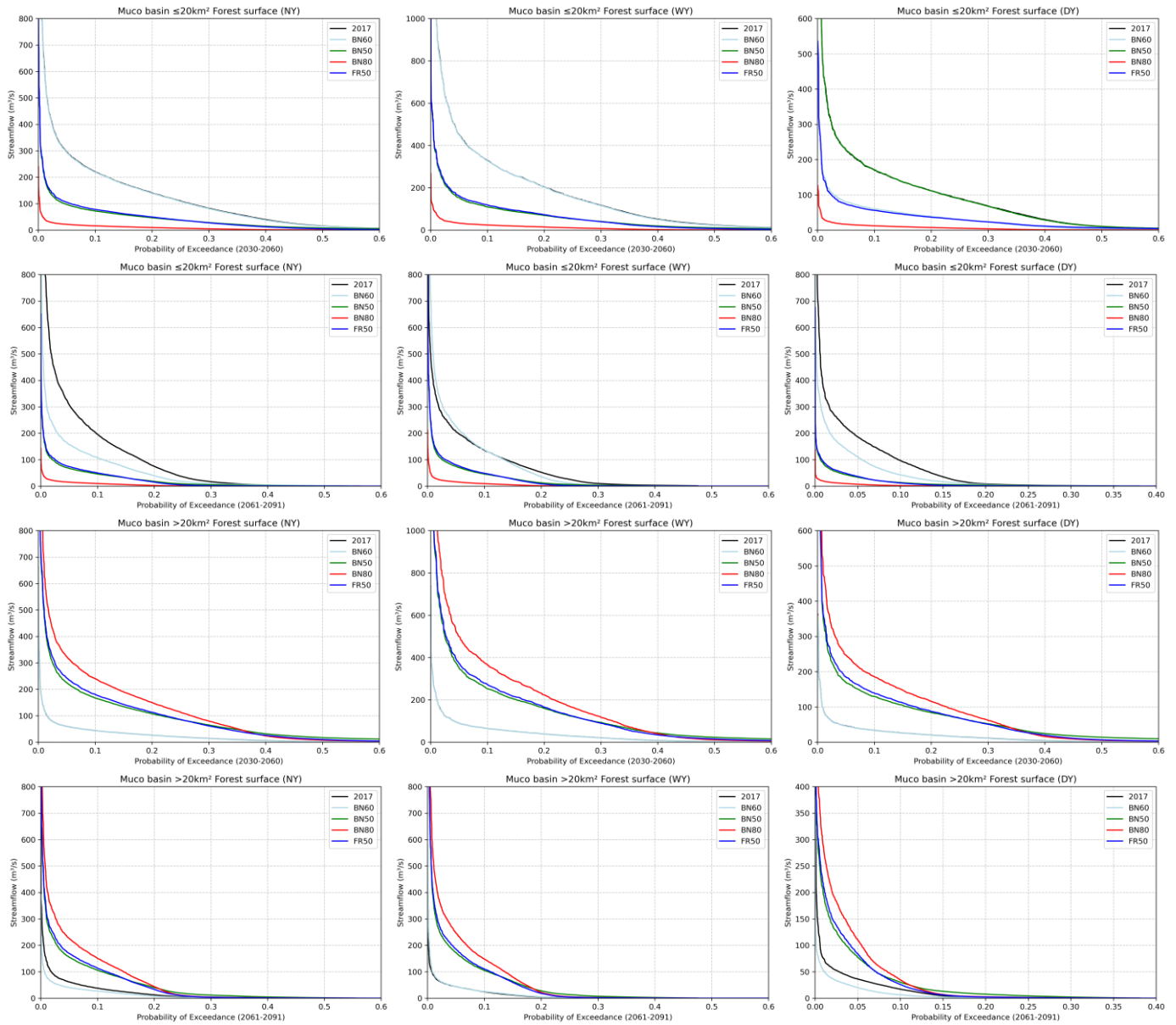
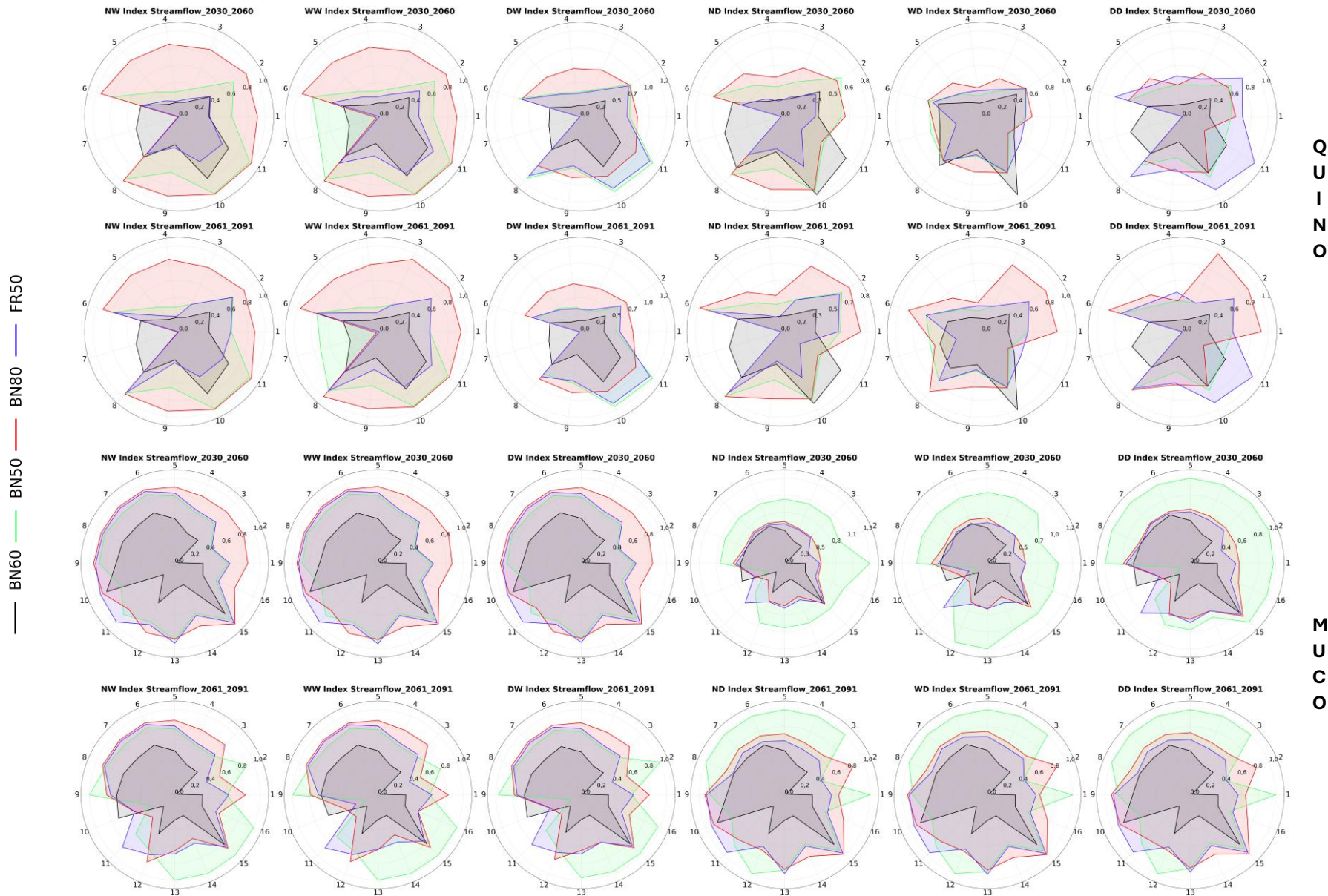


Fig 11 Probability of exceedance (m^3/s) of seasonal streamflow average for basin with forest surface (≤ 20 km² and >20 km²). Natural Year (NY), Wet Year (WY), Dry Year (DY). Muco sub-basin. Period: 2030-2060, 2061-2091

The hydrological performance of the forest index was assessed across wet and dry years. During wet periods, most sub-basins maintain higher flows under the BN80 scenario, followed by BN50 and FR50, compared to the 2017 baseline. In dry periods, BN50 shows improved flow retention, especially in the upper-middle Muco sub-basins. This trend is more pronounced during dry months of wet years. Quino basin shows higher variability, with sub-basins 8 and 10 performing best under BN50 and FR50. In Muco, sub-basins 7, 8, 9, 13, and 15 sustain the highest flows, mainly between 2030–2060 (Fig. 12).



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Fig 12 Hydrological Performance Forest Index. Natural year, wet (NW) dry (ND) seasonal, Wet year, wet (WW) dry (WD) seasonal, Dry year, wet (DW) dry (DD) seasonal. Quino and Muco sub-basin. Period: 2030-2060, 2061-2091

3.6. Impacts on Water Balance of Land Use Change and Climate Change Scenarios Reforestation at the Basin Outlet in Normal, Dry, and Wet Years

A water balance assessment was conducted at the outlets of the Longitudinal (Quino) and Muco (Puente Muco) basins for the periods 2030 - 2060 and 2061 - 2091, with the aim of quantifying hydrological resilience to changes in land cover and analyzing differential responses during normal, wet, and dry years. Although the differences in water balance between the two basins are not substantial when comparing the designed land-use scenarios to the baseline year 2017, the FR50 scenario exhibits a significant reduction in the amount of water retained within the system. This scenario assumes that nearly half of both basins are reforested exclusively in areas previously occupied by forest plantations, replacing native forests, shrublands, and unvegetated soils. This reduction is particularly evident during normal and dry years across both basins. Conversely, the scenario that retains the most water in the system, showing the greatest balance gains for both basins, is BN50, especially during dry years. In some cases, during wet years, the nearly full-basin reforestation scenario (BN80) maintains positive water balance values in the basins. The period 2044 - 2046 exhibited the smallest differences among the scenarios (Fig. 13).

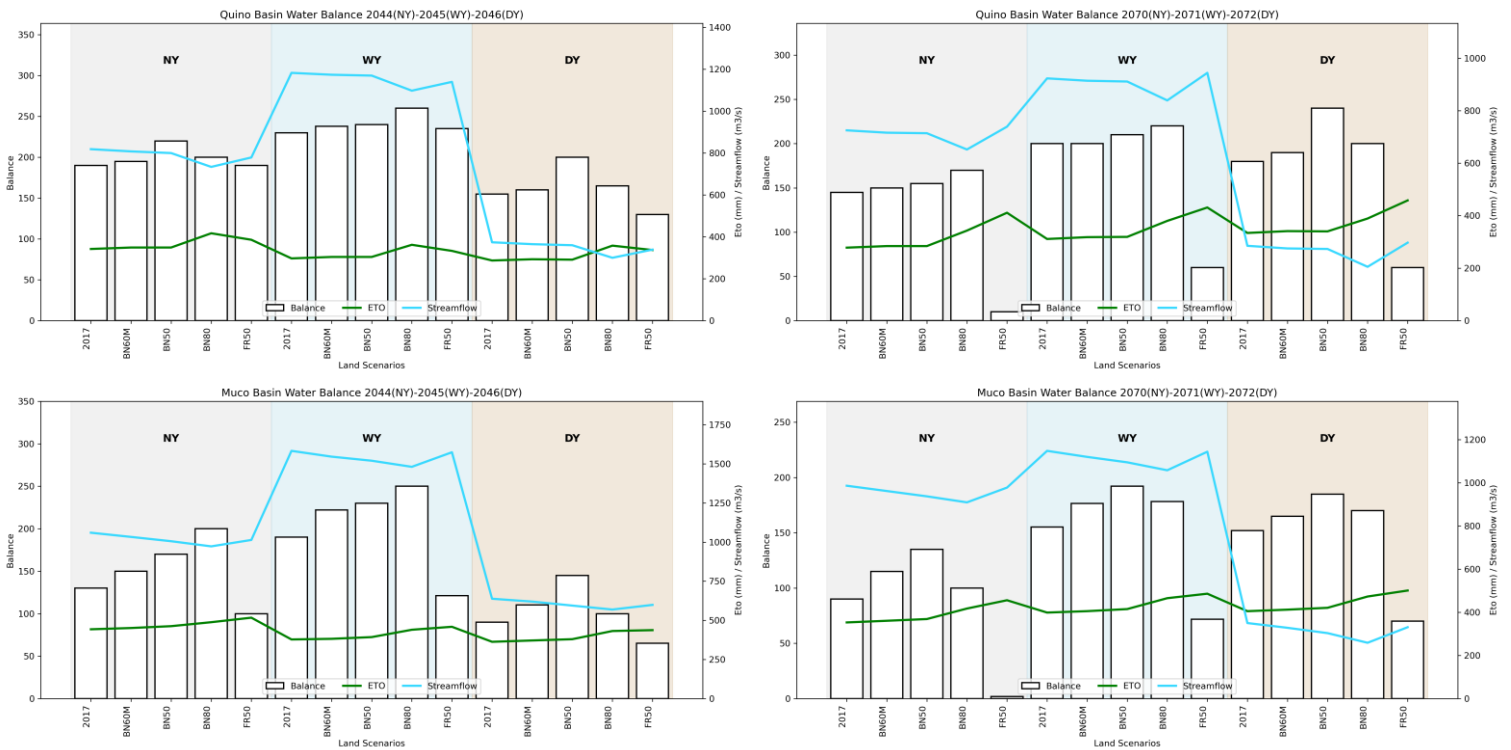


Fig 13 Water Balance (mm). Natural Year (NY), Wet Year (WY), Dry Year (DY).
Quino and Muco. Period: 2030-2091

4. Discussion

4.1. Climate Modeling and Hydrological Projections: Impacts of Climate Change Scenarios on the Water Cycle

This study assessed the combined impact of LUCC and climate change on components of the hydrological cycle in two Chilean watersheds. To evaluate future climate variability particularly extreme precipitation and temperature climate models were selected based on their Taylor Diagram (TD), which accounts for the correlation, standard deviation, and root mean square error between observed data and model simulations for the historical period (1975–2005). Precipitation projections showed high uncertainty and limited ability to reproduce regional variability, consistent with findings by (Vásquez et al., 2025b), who reported similar limitations in CMIP6 models for this region. Nonetheless, CanESM2 exhibited the best performance based on TD. Salazar et al. (2024) evaluated 36 global models over four Chilean climate subregions and identified CanESM5 as the top-performing model for Central Chile, aligning with (Rivera & Arnould, 2020). Although CanESM5 represents a more recent and advanced generation, both models share core structural and conceptual frameworks. This suggests that, for specific variables, the CanESM family provides reliable projections for Central Chile. Moreover, the findings of (Adeliyi et al., 2025) support this choice, as their comparison of CMIP5 and CMIP6 models in simulating monsoon hydrology in Africa concluded that, although CMIP6 offers some improvements, structural limitations persist in both generations particularly in representing regional precipitation variability. This suggests that well-evaluated CMIP5 models, such as CanESM2, remain a valid and robust option for regional contexts like Central Chile. Under climate change scenarios, hydrological model outputs indicated that climate alone could alter hydrological components by approximately 30%. CanESM2 projections suggest reduced precipitation (notably from 2030 - 2060), intensified droughts, and fewer extreme precipitation days (>75th percentile), consistent with (Chawla & Mujumdar, 2015; Vásquez et al., 2025b). Among the isolated impacts, climate has a more dominant effect on water components and projected 30% decline in precipitation across Central Chile is expected to significantly reduce streamflow and other hydrological components, corroborating results from (V. K. Arora et al., 2025; Boisier et al., 2024; Orfi et al., 2025).

Regarding temperature, most models showed strong agreement with observations. The RegCM4 regional model, driven by MPI-ESM-MR (CMIP5), was selected for its higher spatial resolution and better performance, enabling more accurate regional climate assessments. This aligns with (Vásquez et al., 2025b), who used RegCM4 to evaluate snowpack and climate zones under severe warming scenarios in Chile. The model projects a 3°C increase in standardized mean temperature anomalies during both wet and dry seasons, in agreement with (Cortina & Madeira, 2023; Salazar et al., 2024; Vásquez et al., 2025b), who estimate a 2 - 6°C rise under RCP 8.5 and SSP5-8.5 in Central Chile. This warming is mainly attributed to increases in minimum temperatures, leading to a decreased diurnal temperature range, particularly during the dry season. Consequently, future potential evapotranspiration (ET_0) is projected to decline during low-precipitation months compared to historical values. This finding is consistent with (J. Liu et al., 2021). However, trends differ regionally: in countries like China and Australia, ET_0 is expected to rise under extreme scenarios (P. Huang et al., 2023; L. Shi et al., 2020), likely due to regional differences in meteorological drivers or methodological approaches used to estimate ET_0 .

4.2. Effects of land use and change scenarios on water cycle components

Land Use and Cover Change (LUCC) scenarios show an influence of approximately 10% in the percentage change of water cycle components, with streamflow and evapotranspiration showing the greatest changes especially in scenarios with a higher percentage of forested surface. However, the combined effect of both forcings (climate and LUCC) on water cycle components is more pronounced than their individual effects. This is consistent with findings from (Chawla & Mujumdar, 2015; Q. Liu et al., 2020; Lyu et al., 2023b). In those studies, climate change associated with the expansion of urban and forested areas led to significant alterations, particularly in streamflow.

In our research, the AET for all LUCC scenarios considering the total area of native forests and forest plantations tends to decrease during the 2030 - 2090 period. However, when analyzing the actual AET specifically generated by forested areas in the most heavily forested scenarios, an increase is observed compared to the 2017 land use. The smallest difference is found in the scenario where reforestation is restricted to riparian zones, while the largest increase occurs in the scenario with over 50% reforestation of the basin especially through forest plantations

concentrated in the middle and upper sectors of the Quino River basin, particularly during the dry months. This indicates that increased reforestation leads to higher levels of evapotranspiration. This trend is also observed in studies by (H. Chen et al., 2025; S. Sun et al., 2025), which demonstrate that AET increases in response to land cover and use changes, particularly with an increase in forest cover. Even in a scenario where nearly the entire basin is restored with native forest, the actual AET remains lower than in the scenario involving only forest plantations. This was also demonstrated by (Jiao et al., 2024), who showed that AET increases especially in evergreen forests including species like *Pinus radiata* due to high transpiration, canopy interception, and denser vegetation cover.

In the case of streamflow, various analyses were conducted, as this variable has shown high sensitivity to landscape modifications, particularly those related to native forests and seasonal periods, as indicated by (Hernández-Sosa et al., 2025). When analyzing streamflow alone, the most pronounced differences were observed during dry periods at the sub-basin scale. The Muco catchment exhibited the highest streamflow values when the upper part of the basin was reforested with native forest (BN50), whereas the Quino catchment displayed greater variability in its hydrological responses. Regarding flow exceedance percentages, the analysis was carried out for wet, dry, and normal years, focusing on sub-basins with the highest and lowest forest cover. The results showed minimal differences overall; however, in sub-basins with higher forest cover, the BN80 scenario was the most effective in buffering streamflows. These findings are consistent with (X. Ma et al., 2024), who demonstrated that the loss of native forest leads to a significant decline in streamflow. Similarly, Valencia et al. (2024), through a seasonal analysis, concluded that greater forest cover particularly native forest enhances streamflow during the dry season, supporting the outcomes of this study.

To further evaluate the hydrological impact of reforestation, an integrated index was developed, combining sub-basin area, forested area, and both expected and simulated streamflows to assess water generation capacity under increased forest cover. This index includes accumulated information from tributaries, aiming to evaluate whether a basin can maintain or improve its hydrological contribution despite streamflow variations under scenarios of increased forest cover. The analysis encompassed wet, dry, and normal years, as well as their respective seasonal periods, with the most significant effects associated with wet and dry periods. The BN80

restoration scenario performed best during wet years and seasons, while the BN50 (Muco) and FR50 (Quino) scenarios were more effective during dry years and seasons, particularly in mid-to-upper basin zones. These results are consistent with previous research (Little et al., s. f.; Pizarro et al., 2022), which demonstrated that increased native forest cover improves both streamflow and water productivity compared to forest plantations. Finally, the water balance at the outlet of both catchments showed slight differences among the various land use and cover change scenarios. Throughout the analyzed years, the scenario with the lowest water retention capacity was the one reforested solely with forest plantations. Conversely, the BN80 and BN50 scenarios exhibited the highest water retention, especially during the dry year of the 2070 - 2072 period, where a marked trend of decreasing precipitation was observed.

4.3. Application in territorial planning, watershed management, and climate adaptation strategies considering LUCC scenarios

In Chile, there is a marked trend toward the expansion of forest plantations and urban areas, along with a reduction in agricultural lands and native forests (Aguayo et al., 2009b; Benavidez-Silva et al., 2021; Echeverría et al., 2012b; Heilmayr et al., 2016b; Hernández-Sosa et al., 2025; Martínez-Retureta et al., 2020b; Rodríguez-Echeverry et al., 2018b). Rural land has been urbanized without effective control, including areas unsuitable for construction, following the current neoliberal model of territorial occupation. This model lacks sustainable planning and leads to land-use fragmentation, illegality, and conflicts (Benavidez-Silva et al., 2021). Numerous studies in Chile have demonstrated that the increase in urban-forestry zones has resulted in ecological isolation, habitat and ecosystem services loss, increased natural disasters, and the loss of agricultural lands due to various socio-economic pressures, thereby elevating the risk of food insecurity and affecting the water cycle at the watershed scale (Argandoña-Castro & Peña-Cortés, 2025; Benavidez-Silva et al., 2021; Del Pozo et al., 2024; Hernández-Sosa et al., 2025; Martínez-Retureta et al., 2020b). Therefore, it is essential to reconsider an integrated territorial planning model or integrated watershed management approach that accounts for: agricultural land demand, conservation of ecosystem services, urban-forestry expansion, and climate change adaptation. This new planning paradigm is inherently complex, as it must consider biophysical, economic, regulatory, and geospatial factors and integrate multi-scale and cross-sectoral indicators (Argandoña-Castro & Peña-Cortés, 2025; Benavidez-Silva et al., 2021).

In our research, reforestation scenarios at small and large scales were developed for two sub-watersheds with the objective of assessing the combined impact of climate change and landscape transformation on hydrological regulation. The formulation of these scenarios incorporated various criteria, including Nature-Based Solutions (NbS), land-use planning policies, Chilean native forest protection legislation, and social considerations. Specifically, the analysis included perceptions gathered from surveys conducted with communities in the south-central region of the country (Little et al., 2015.). According to these local testimonies, the reduction in river flows is attributed to the expansion of exotic forest plantations. Respondents noted that when native forests dominated the landscape, water availability was higher, and that river flows tend to recover following wildfires that destroy extensive plantation areas.

The proposed scenarios constitute a preliminary contribution toward the formulation of integrated land-use planning policies and offer a robust foundation for the development of future models of land cover and land-use change. The findings indicate that increased reforestation with native species does not significantly reduce water flows; on the contrary, it may enhance hydrological regulation at the watershed scale, even under projected conditions of increased aridity. This dynamic contrasts with that observed in exotic forest plantations, which tend to reduce water availability. Likewise, the conservation of agricultural soils and ecological restoration in the upper areas of watersheds emerge as effective strategies to improve the water balance, particularly under drier climate scenarios. Moreover, some scenarios that retain agricultural land use and promote reforestation of over 50% of watershed areas primarily in the mid-to-upper basin may indirectly support the provision of other key ecosystem services, such as food security, carbon sequestration, and cultural services (Benra et al., 2019; Jung & Vendrametto, 2025; Londres et al., 2023; Rapiya et al., 2024).

However, the evaluated scenarios do not constitute definitive proposals for land management. Advancing toward more comprehensive approaches will require the design of more complex models that simultaneously consider: (1) the inevitable expansion of economic activities in a strategic manner, avoiding unregulated sprawl and anticipating growth (Benavidez-Silva et al., 2021); (2) inclusive policies for vulnerable sectors, such as the integration of ancestral knowledge from the Mapuche People for native forest conservation and improve collaboration between actors (Tapia et al., 2025; Vocht & Dias, 2024); and (3) the implementation of robust regulatory

policies, supported by scientific evidence, to anticipate, minimize, and mitigate the impacts of landscape transformation on ecosystem services (Albert et al., 2014; Congreve & Cross, 2019). Under these guiding principles, it is possible to move toward an integrated strategy for territorial planning and watershed management. Urban–forestry development must not come at the expense of the environment or social equity, but rather should aim to balance economic growth, social inclusion, and environmental sustainability.

4.4. Uncertainty and Limitation

Although the TETIS model has demonstrated robust performance in simulating hydrological processes and projecting future streamflow's, several sources of uncertainty remain that warrant careful consideration. One such source lies in the model's limited ability to accurately represent different vegetation types within land cover and land use maps, particularly in distinguishing between native forests and commercial forest plantations. Currently, this differentiation is primarily based on parameters such as the vegetation factor, canopy interception, root depth, and static soil water storage. However, a more precise characterization of the ecohydrological differences between these forest types would require the incorporation of additional variables, such as phenological cycles and canopy structural diversity. For instance, forest plantations could be modeled as rotational agricultural systems with periodic growth and harvest cycles (typically around 10 years), in contrast to native forests, which maintain perennial cover and exhibit slower, continuous growth. Moreover, integrating the structural complexity of native forest canopies characterized by multiple vertical strata (herbaceous, shrub, and arboreal) as opposed to the structural homogeneity of plantations, would enhance the model's ability to realistically simulate ecohydrological processes. These refinements would support more informed land-use planning by promoting the coexistence of productive land uses and the conservation of native ecosystems, while accounting for their respective impacts on watershed water balance. A second relevant source of uncertainty concerns the estimation of reference evapotranspiration (ET_0). In the Penman-Monteith equation, which incorporates variables such as mean temperature, relative humidity, and wind speed, mean temperature often emerges as the dominant factor influencing future potential ET_0 estimates. In contrast, the Hargreaves equation places greater emphasis on temperature extremes. These methodological differences partially explain the variation in ET_0 responses under warming scenarios observed across different geographic regions. As such,

careful consideration of these factors is essential, as they may significantly influence model accuracy and its applicability for water resource planning and decision-making.

Another key consideration is the challenge of effectively integrating Nature-based Solutions (NbS) into territorial planning models. Although these strategies have been widely endorsed at the international level, their practical implementation still faces significant limitations. This is largely due to the fact that many existing guidelines remain overly general and lack operational specificity. While there are successful case studies and methodologies that can serve as useful references for NbS implementation, few studies rigorously assess the effectiveness of these interventions in restoring or buffering ecosystem services particularly in rural areas. Moreover, most of these studies do not specify critical technical parameters, such as the minimum riparian buffer width required for reforestation, the percentage of native forest cover that should be preserved in headwater areas, or spatial prioritization criteria specifically aimed at water regulation and provisioning services within watersheds. In several cases, the authors themselves acknowledge that a substantial gap still exists in achieving effective and systematic implementation of these solutions (De Mendonça et al., 2025; Marijuan et al., 2024; Panaro et al., 2025). The absence of practical, context-specific guidance hinders informed decision-making in territorial planning processes. For instance, the Nature-Based Solutions Implementation Handbook developed IUCN. (2020), provides a general framework for NbS implementation, yet it lacks detail regarding selection criteria and applicability across diverse territorial contexts. While it is necessary to assess each territorial context individually, it is equally essential to develop more concrete and adaptable methodological guidelines that support decision-making and enable the integration of NbS into public policies and land-use or integrated watershed management planning.

5. Conclusion

This study highlights the complex interplay between climate change, land use and cover change (LUCC), and hydrological processes in Central Chilean watersheds. Climate change alone is projected to significantly alter hydrological components, with temperature increases and declining precipitation leading to reduced streamflows and modified evapotranspiration patterns.

LUCC scenarios, particularly those involving large-scale reforestation with native species, demonstrate potential to buffer some of these impacts, enhancing hydrological regulation during dry periods. Notably, native forests outperformed exotic plantations in water retention and ecosystem service provision. However, the combined effects of climate and LUCC are more pronounced than their isolated impacts, underscoring the need for integrated modeling approaches. Despite robust model performance, key uncertainties persist, particularly in ecohydrological differentiation between vegetation types and the estimation of AET under warming scenarios. Additionally, the effective implementation of Nature-based Solutions (NbS) is constrained by the lack of operational guidance tailored to specific territorial contexts. Bridging this gap requires the development of more detailed, context-sensitive methodologies and regulatory frameworks to support integrated land-use and watershed management. Ultimately, this research provides a scientific foundation for guiding climate adaptation strategies and informing policy decisions that seek to harmonize ecological conservation, water security, and sustainable territorial development.

Author contributions

Marieta Hernández-Sosa: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Mauricio Aguayo: Writing – review & editing, Validation, Supervision, Methodology. Nicolas Cortes: Writing – review & editing, Software, Methodology. Alejandra Stehr: Writing – review, Validation, Supervision, Methodology. Felix Frances: Writing – review, Validation, Supervision, Methodology. Ovidio Llompart: Writing – review & editing, Software, Visualization.

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Declaration

Conflict of interest The authors declare that they have no conflict of interest.

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CAPÍTULO VI. DISCUSIÓN GENERAL

VI.1. Análisis Simulado del Comportamiento Climático e Hidrológico

Esta investigación evaluó el impacto combinado del cambio en la cobertura y el uso del suelo, junto con el cambio climático, sobre el ciclo hidrológico en dos sub-cuencas chilenas. Los datos climáticos actuales y futuros fueron obtenidos de la base de datos CR2. La selección de modelos se basó en análisis mediante diagramas de Taylor, utilizando simulaciones del conjunto CMIP5. Para la precipitación se utilizó el modelo CanESM2, mientras que para las temperaturas extremas se empleó el modelo regional RegCM4. Las proyecciones climáticas futuras se desarrollaron bajo el escenario de cambio climático RCP8.5, con el objetivo de demostrar cómo, incluso bajo condiciones extremas, nuevos escenarios de reforestación pueden atenuar los efectos adversos de esta forzante sobre los componentes del ciclo del agua y favorecer una mayor retención hídrica del sistema. Las proyecciones de precipitación confirman lo señalado por numerosos estudios: la modelación climática aún presenta limitaciones importantes para replicar con precisión los valores observados (Vásquez et al., 2025). No obstante, el modelo CanESM2 ha sido identificado, tanto en investigaciones previas como en el presente estudio, como uno de los más precisos para simular la precipitación en la zona centro de Chile (Rivera & Arnould, 2020; Salazar et al., 2024). Las proyecciones indican una reducción del 30 % en las precipitaciones para el periodo 2030–2060, con una menor frecuencia de eventos extremos y un incremento en la ocurrencia de sequías. Estos resultados se alinean con la mayoría de los estudios sobre cambio climático en la región, los cuales estiman reducciones de hasta un 40 % en las precipitaciones (Araya-Osses et al., 2020b; Garreaud et al., 2020). Para el análisis de temperaturas extremas, se seleccionó el modelo regional RegCM4, impulsado por MPI-ESM-MR (CMIP5), debido a su mejor desempeño, lo que permite realizar evaluaciones climáticas regionales con mayor precisión. A partir de este modelo, se proyecta un aumento de hasta 3 °C, especialmente en las temperaturas mínimas, lo que reduciría la amplitud térmica diaria y afectaría la evapotranspiración (ET_0), que tendería a disminuir durante los meses más secos, según la ecuación de Hargreaves, en concordancia con lo planteado por (J. Liu et al., 2021).

La modelación hidrológica se llevó a cabo utilizando el modelo TETIS, que mostró un buen desempeño durante los procesos de calibración y validación en ambas cuencas, Quino y Muco.

Las métricas de evaluación, como NSE, PBIAS y RSR, se ubicaron dentro de los rangos considerados como “muy buenos” según los criterios propuestos por (Moriasi, 2015), lo que indica un adecuado ajuste entre las observaciones y las simulaciones. Estos resultados coinciden con estudios previos realizados en la región, como los de (Martínez-Retureta et al., 2020) y (Barrientos et al., 2020). La precisión del modelo se ve influenciada por factores como la escasa cobertura de estaciones meteorológicas en las zonas altas de Chile (Benra et al., 2019), así como por la calidad de algunos mapas base, por ejemplo, los relacionados con la capacidad de percolación del suelo. Un aspecto clave fue el ajuste del parámetro FC2 (evapotranspiración), cuyos valores elevados podrían explicarse por las características edáficas de la zona (alta capacidad de retención hídrica) y por la presencia dominante de plantaciones forestales, que incrementan la evapotranspiración (Balocchi et al., 2020; Berg et al., 2014; Oyarzún, 1999). A pesar de algunas limitantes asociadas al modelo, como factores correctores o mapas bases; que pudieran ser ajustados en estudios futuros. Se concluye que el modelo TETIS constituye una herramienta robusta, capaz de estimar con detalle espaciotemporal la relación entre los componentes del ciclo hidrológico y la composición-configuración del paisaje en cuencas del centro-sur de Chile.

VI.2. Influencia de la Configuración del Paisaje y del Cambio de Cobertura y Uso del Suelo sobre el Ciclo Hidrológico.

Desde 1986, el paisaje de las cuencas estudiadas ha experimentado una notable transformación, marcada principalmente por la expansión de la agricultura y de plantaciones forestales, lo que ha simplificado la estructura espacial del territorio y reducido significativamente la conectividad ecológica. Esta modificación ha tenido efectos directos sobre el ciclo del agua, particularmente en el aumento de la evapotranspiración y en la pérdida de agua durante la temporada húmeda, coincidiendo con (Yohannes et al., 2021). A partir de la relación entre configuración y composición del paisaje podemos determinar que: El aumento de las plantaciones forestales, desarrollado de forma agregada y, en muchos casos, sobre superficies de bosque nativo, ha generado importantes efectos sobre el ciclo hidrológico. En particular, se ha observado que las plantaciones jóvenes tienden a correlacionarse negativamente *con métricas de contraste*, como el contraste de bordes (ECON), a nivel de parche, lo que se asocia con una disminución en procesos hidrológicos verticales como la evapotranspiración, la infiltración y la percolación

(Balocchi et al., 2020; Huber et al., 2010). Por otra parte, métricas de agregación como *el número de parche* y métricas de forma como la *contigüidad espacial* a nivel de clase correlaciona positivamente con caudales y procesos hidrológicos específicamente con los bosques nativos. Lo cual se pudiera traducir en que la pérdida de los bosques nativo a escala de clase genera un efecto contrario, a lo que provoca la presencia de plantaciones exóticas en componentes del ciclo del agua (Haas et al., 2022; Lyu et al., 2023). El análisis de Regresión de Mínimos Cuadrados Parciales (PLSR, por sus siglas en inglés), destaca como el número de parches pudiera ser la variable de mayor importancia para explicar las variaciones entre superficie de bosque y caudal. Mientras que para los procesos hidrológicos las métricas ENN, PROX y CONT son las variables explicativas de mayor importancia con los usos de suelo de bosques. Esto refleja la relevancia que tiene la agregación del paisaje para establecer la relación entre configuración-composición del paisaje y componentes del ciclo del agua.

A partir de estos resultados, y considerando la integración de soluciones basadas en la naturaleza junto con políticas nacionales de protección del bosque nativo, entre otros factores. Se construyeron cuatro escenarios de cambio de cobertura y uso del suelo para analizar el impacto de esta forzante en el ciclo hidrológico, sumando además el estrés generado por la reducción proyectada de las precipitaciones. El cambio climático se identificó como el principal modulador de las variaciones en el caudal y la evapotranspiración, mientras que los cambios en la cobertura y uso del suelo produjeron alteraciones cercanas al 10 %. Sin embargo, fue la combinación de ambas forzantes la que generó los efectos más significativos sobre el sistema hidrológico. El análisis integrado demostró que, aunque la evapotranspiración de referencia tiende a disminuir bajo escenarios futuros, la evapotranspiración de la superficie de usos, simulada por el modelo, se incrementa en áreas con mayor cobertura de bosque, especialmente en zonas reforestadas con plantaciones exóticas. Este aumento es más evidente durante los meses secos, debido a la mayor transpiración e interceptación de especies como *Pinus radiata*, en comparación con los bosques nativos, lo cual fue demostrado por (Jiao et al., 2024).

El caudal, por su parte, mostró alta sensibilidad a la composición del paisaje. Escenarios de restauración con una mayor proporción de bosque nativo, como BN50 (586 km²) y BN80 (841km²), para ambas cuencas, presentaron una mayor capacidad de retención durante los

periodos secos, así como una mejor regulación del caudal. Un índice integrado, que considera área, cobertura forestal y caudal simulado, respalda estos resultados, indicando que los escenarios BN80 y BN50 poseen la mayor capacidad de retención de agua, mientras que aquellos dominados exclusivamente por plantaciones forestales presentan menor retención, en línea con los hallazgos de (Balocchi et al., 2020). En contraste, la reforestación limitada únicamente a las zonas de ribera no evidenció diferencias significativas en el comportamiento de la evapotranspiración y el caudal, en comparación con el escenario de uso de suelo del año 2017.

VI.3. El Impacto de los Cambios de Cobertura y Uso de Suelo para la Planificación Territorial, Gestión de Cuencas y Adaptación Climática.

Chile enfrenta una creciente presión sobre su territorio debido a la expansión no planificada de plantaciones forestales y procesos de urbanización, lo que ha resultado en la pérdida de suelos agrícolas, fragmentación del paisaje y una marcada desconexión ecológica. Estas transformaciones han disminuido la provisión de servicios ecosistémicos, aumentado la vulnerabilidad frente a desastres naturales y comprometido tanto la seguridad alimentaria como la funcionalidad del ciclo hidrológico. En este contexto, podemos asegurar que se hace necesaria una planificación territorial orientada a la adaptación al cambio climático donde se integren factores espaciales, culturales, de gobernanza y socioeconómicos (Galan et al., 2023). Las métricas del paisaje emergen como herramientas de configuración espacial fundamentales para vincular la gestión de cuencas con la adaptación climática, ya que se ha logrado determinar cómo la combinación de los patrones del paisaje con la cobertura en superficie afectan los procesos hidrológicos (Marijuan et al., 2024; Yohannes et al., 2021). Esta investigación destaca que la conservación y restauración de bosques nativos de forma agregada desempeña un papel clave en la regulación hídrica. Mientras que prácticas forestales, igualmente agregadas, conectadas, intensivas y homogéneas alteran fundamentalmente procesos hidrológicos como la evapotranspiración (Song et al., 2023).

Un aspecto metodológico relevante en este estudio fue la decisión de agrupar las coberturas vegetales en categorías amplias, como bosque nativo, plantaciones forestales y pastizales, lo cual se justificó principalmente por la necesidad de simplificar el análisis espacial y reducir la incertidumbre ante la respuesta hidrológica por las transformaciones del paisaje. No obstante, esta homogenización puede ocultar variaciones importantes dentro de cada tipo de cobertura,

especialmente en el caso de los matorrales y los distintos grados de densidad de los bosques nativos, que presentan respuestas ecológicas e hidrológicas diversas. La exclusión de los matorrales de los escenarios principales de restauración se basó en una evaluación crítica de sus limitaciones. En contextos de que en zonas de mayores riesgos de aumento de temperatura también se asocian con un mayor riesgo de incendios, lo que representa una amenaza significativa en términos ambientales y de gestión del territorio (Lutz et al., 2017). Por otra parte, la simplificación del paisaje al agrupar coberturas en grandes clases permitió explorar de forma más clara cómo la composición y configuración del paisaje influyen sobre los procesos hidrológicos, especialmente en escenarios de restauración a gran escala. Este enfoque ayuda a disminuir el nivel de incertidumbre respecto a la pregunta central del estudio: ¿los bosques nativos ofrecen mejores beneficios hidrológicos que las plantaciones forestales? En este sentido, muy pocas investigaciones abordan procesos de restauración ecológica a escala de cuenca, por lo que este estudio aporta evidencia relevante y genera una base para discusiones futuras. Finalmente, si bien un análisis más desagregado podría ofrecer mayor detalle sobre los efectos de la fragmentación del paisaje, es importante reconocer que escenarios altamente fragmentados como el del actual uso del 2017 genera más incertidumbre en los resultados. Por ejemplo, aunque se observó que las plantaciones forestales tienden a aumentar la infiltración cuando se agregan en el paisaje, la pérdida de bosque nativo reduce este proceso, generando ambigüedades difíciles de resolver sin ampliar el marco de análisis. En consecuencia, esta discusión no solo refuerza la necesidad de evaluar los escenarios de restauración desde una perspectiva integral del paisaje, sino que también plantea líneas de investigación futuras orientadas a descomponer la respuesta hidrológica según distintas configuraciones de uso y cobertura del suelo, y en contextos con diferentes regímenes climáticos.

Es por ello que, el diseño de cuatro escenarios de restauración-conservación de bosque nativo basados en criterios interdisciplinarios (políticos, socioeconómicos y ambientales), en contexto chileno, demostró que: Aunque las diferencias no sean tan marcadas entre escenarios y que, evidentemente el cambio climático es el principal modulador de los cambios en los componentes del ciclo del agua. Se aprecia como la reforestación con especies nativas a gran escala mantiene mayor cantidad de agua dentro del balance que las asociadas con las plantaciones forestales entre (100-50 mm). Coincidiendo con los estudios que aseguran que las pérdidas de esta superficie han dañado numerosos componentes del ciclo del agua, incluyendo el caudal (Haas et al., 2022; Lyu

et al., 2023; Renée Brooks et al., 2010). Por el contrario, mejora la regulación hídrica, especialmente bajo condiciones de mayor aridez. Mientras que la restauración considerando solo plantaciones forestales, tiene mayores tasas de evapotranspiración, menos caudal y menos agua retenida en el balance de agua. Estos hallazgos ofrecen una base científica preliminar para el desarrollo de políticas públicas y planificación territorial climáticamente inteligentes. No obstante, es necesario avanzar hacia una modelación hidrológica más compleja e integradora, que consideren: La expansión económica sostenible, la inclusión de saberes ancestrales, y marcos regulatorios sólidos respaldados por una mayor evidencia científica (Botero-Acosta et al., 2022).

Adicionalmente, se recomienda mejorar la calidad y precisión de las variables de entrada en el modelo TETIS, especialmente aquellas que generan incertidumbre en la diferenciación funcional entre tipos de cobertura forestal, tales como los ciclos fenológicos. También se sugiere revisar críticamente los métodos de estimación de la evapotranspiración de referencia, considerando la variabilidad entre modelos climáticos, e incorporar enfoques de ensambles climáticos. Para asegurar captar con mayor seguridad el comportamiento futuro de esta variable en la región. Finalmente, aun es necesario el desarrollo de guías metodológicas claras, adaptables y operativas, que faciliten la incorporación efectiva de las SbN en los instrumentos de planificación y gestión territorial, fundamentalmente asociado a la preservación del agua, a partir de la preservación de los bosques.

CONCLUSIONES GENERALES.

Los resultados obtenidos evidencian que el modelo hidrológico TETIS presentó un desempeño sobresaliente en la simulación de procesos hidrológicos diarios en las cuencas de estudio, cumpliendo e incluso superando los estándares de calidad establecidos por la literatura científica (Moriassi et al., 2007, 2015). A pesar de las limitaciones geográficas y climáticas del contexto chileno como la baja densidad de estaciones meteorológicas en zonas de montaña, los indicadores de ajuste (NSE, PBIAS y RSR) demostraron una adecuada calibración y validación del modelo. Paralelamente, se observó que la configuración y composición del paisaje tienen un impacto directo y significativo sobre los componentes del ciclo hidrológico. Métricas como el número de parches (NP), el índice de proximidad (PROX), el índice de contigüidad (CONT)

y la distancia al vecino más cercano (ENN) mostraron fuertes correlaciones con variables hidrológicas clave, incluyendo la evapotranspiración, la infiltración y el caudal.

La expansión de plantaciones forestales de especies exóticas como *Eucalyptus* y *Pinus* ha incrementado las tasas de evapotranspiración alrededor de 15-20 mm, evidenciando un efecto adverso sobre la regulación hídrica. En contraste, la restauración del bosque nativo, sobre todo en las zonas medias y altas de las cuencas, mostró un efecto amortiguador que mejora la retención hídrica y reduce las pérdidas durante meses más secos entre 20-100 mm, atendiendo al período estacional y el año analizado. Estos resultados subrayan cómo la fragmentación, la pérdida de conectividad y la homogeneización del paisaje debido a la expansión forestal alteran significativamente el balance hídrico. Las métricas de agregación y forma de los parches emergen como las más relevantes para explicar esta dinámica, lo que pone de manifiesto la necesidad de mantener paisajes nativos conectados para preservar los servicios ecosistémicos hídricos.

Asimismo, se destaca la utilidad de integrar métricas de paisaje en estrategias de manejo de cuencas y en políticas de adaptación al cambio climático. En este contexto, la conservación y restauración del bosque nativo se posiciona como una acción clave para sostener la provisión de servicios hídricos. Se plantea la importancia de diseñar escenarios futuros de cambio de uso del suelo que incorporen tanto la configuración como la composición del paisaje, junto con factores sociales y soluciones basadas en la naturaleza (NbS), como herramientas para una planificación territorial efectiva y sostenible. Esta necesidad se vuelve aún más crítica considerando las proyecciones climáticas que anticipan una disminución en la precipitación, un aumento en la frecuencia de sequías y una menor ocurrencia de eventos de lluvia extrema, especialmente entre 2030 y 2060. Estas condiciones podrían reducir el caudal hasta en un 30% y comprometer la disponibilidad de agua.

Por otro lado, los escenarios de cambio de uso de suelo (LUCC) generaron una variación de aproximadamente un 10% en los componentes hidrológicos, con impactos notables sobre la evapotranspiración real y el caudal, especialmente cuando se produce un aumento de la cobertura forestal. En particular, los escenarios de restauración con alta cobertura de bosque nativo (BN80 y BN50) mostraron un mejor desempeño hidrológico que aquellos dominados por plantaciones exóticas, principalmente durante los períodos secos. En conjunto, los impactos

combinados del cambio climático y del cambio de uso del suelo resultan ser mayores que los efectos individuales, afectando de manera más severa la regulación del caudal en épocas críticas.

Aunque el indicador combinado que integra área, superficie forestada y relación entre caudal forestado y esperado no permitió establecer una relación concluyente a escala de cuenca. Los resultados sugieren que restauraciones focalizadas en zonas medias-altas, particularmente del orden de 5 a 10 km² podrían contribuir a una mejora en los caudales. Este patrón se evidenció bajo los escenarios BN50 y FR50, donde dichas superficies restauradas parecieran asociarse a una mayor estabilidad hidrológica. No obstante, debido a que el análisis del balance de agua a nivel de cuenca se realizó a escala de salida de cuenca y para años representativos, se optó por no generalizar esta observación como una conclusión definitiva. Se plantea, por tanto, como una hipótesis prometedora que requiere validación mediante estudios con mayor resolución espacial y temporal, aspecto que ha sido incorporado como recomendación clave en las conclusiones generales del estudio.

Finalmente, se subraya la urgencia de implementar modelos de planificación territorial integrados que consideren la conservación del suelo agrícola, la protección de ecosistemas nativos, el control del desarrollo urbano y las proyecciones climáticas. Estas estrategias deben incorporar criterios sociales y de gobernanza, incluyendo la participación de comunidades locales y pueblos originarios. No obstante, persisten limitaciones en la capacidad de los modelos actuales como TETIS para diferenciar entre tipos de cobertura forestal y simular procesos eco-hidrológicos complejos. A pesar del potencial de las soluciones basadas en la naturaleza para restaurar servicios ecosistémicos y mejorar la gestión del agua, su implementación enfrenta barreras debido a la falta de lineamientos técnicos adaptados al contexto local. Por ello, es fundamental avanzar hacia directrices claras y operativas que orienten su aplicación efectiva en la gestión de cuencas y la planificación territorial.

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