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Vulnerable Waters

Watershed human pressures on water quality and freshwater ecosystem services in the central Andes of Bolivia

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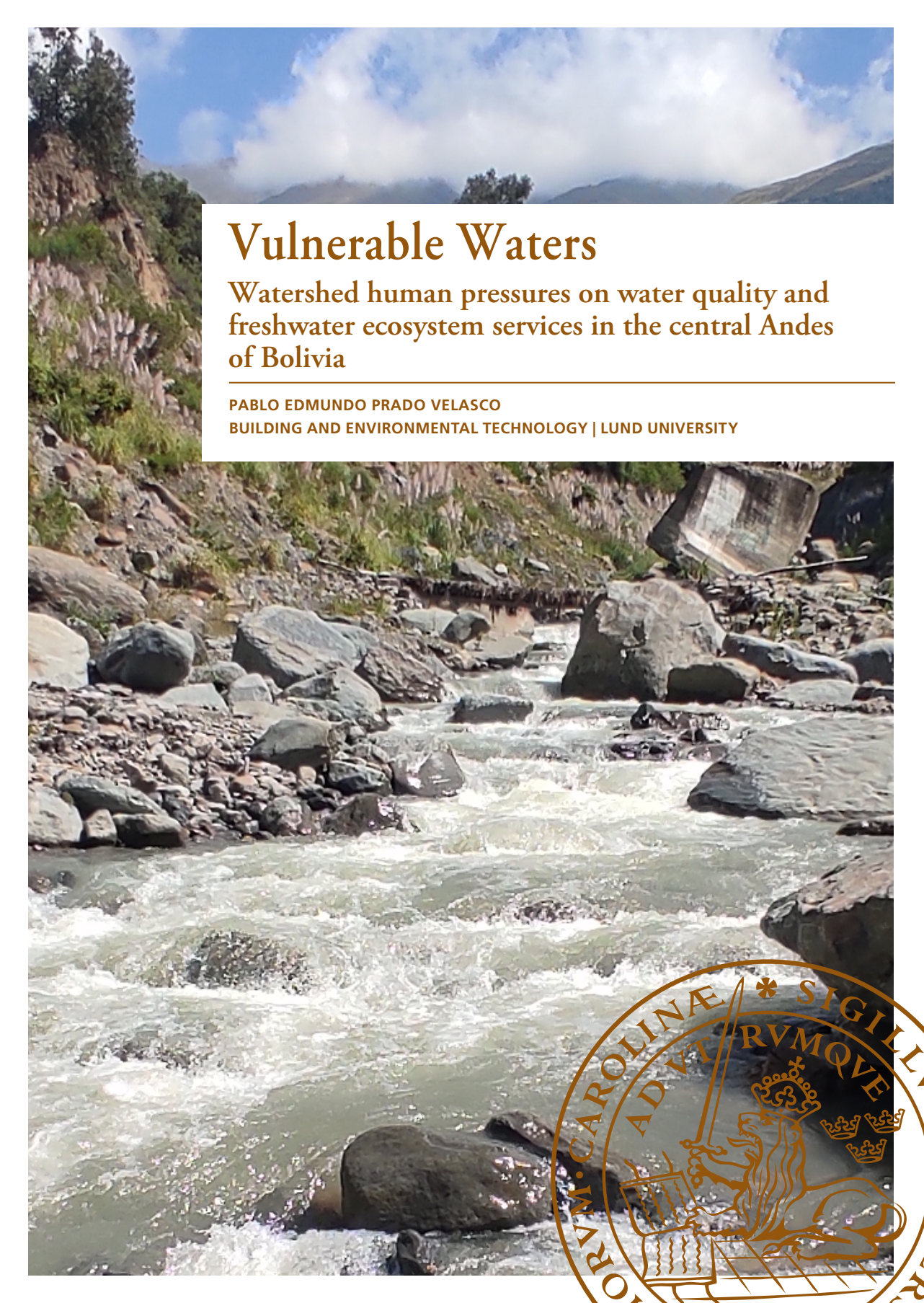
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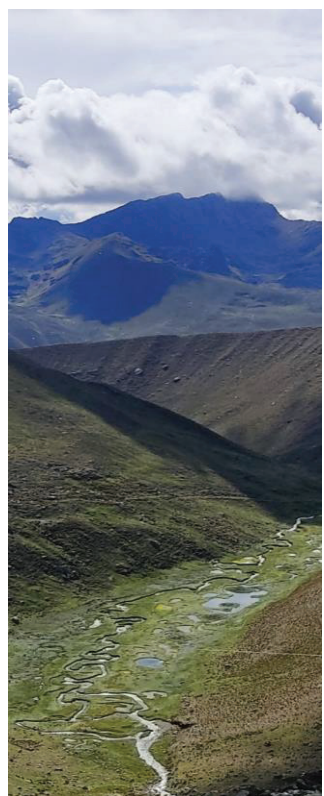
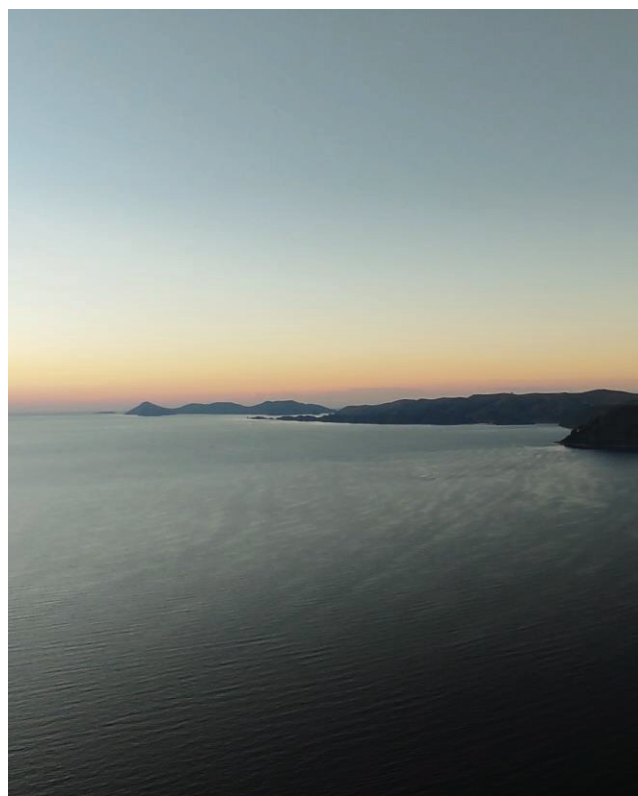
Watershed human pressures on water quality and freshwater ecosystem services in the central Andes of Bolivia

PABLO EDMUNDO PRADO VELASCO

BUILDING AND ENVIRONMENTAL TECHNOLOGY | LUND UNIVERSITY



Vulnerable waters: Watershed human pressures on water quality and freshwater ecosystem services in the central Andes of Bolivia





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Bolivia

Pablo Edmundo Prado Velasco



LUND
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Abstract:

High-altitude lakes and headwater streams of the Andes provide essential benefits to society, yet they remain among the least studied and most vulnerable freshwater ecosystems. These systems supply drinking water, support agriculture and grazing, regulate floods, store carbon, and hold deep cultural and spiritual value for local communities. However, climate change, land use change, water extraction, and limited wastewater treatment are rapidly altering these environments, particularly in the Central Andes of Bolivia, where steep terrain and fragile ecosystems intensify human and environmental pressures.

This thesis develops an interdisciplinary framework to assess how environmental change and land use / land cover affect water quality and related freshwater ecosystem services across spatial scales. The study integrates satellite remote sensing, field measurements, global environmental databases, hydrological and machine-learning models, and surveys of local perceptions. At the regional scale, the research contributes to the characterisation and classification of Andean lakes, identifying distinct "lake districts" and highlighting significant gaps in monitoring across the continent. At the watershed scale, analyses show that anthropogenic land use / land cover and rainfall explain more than 60% of variability in stream water quality, while water diversions and irrigation can obscure natural processes such as dilution and nutrient retention. At the lake scale, satellite data combined with field observations provide indicators of trophic state and carbon dynamics, helping detect ecological change in small high-altitude lakes.

The research also examines how local communities perceive freshwater ecosystem services. Survey results indicate that water provisioning, climate regulation, and cultural values are considered the most important benefits, with perceptions strongly influenced by proximity to freshwater ecosystems, environmental conditions, and socioeconomic factors.

By integrating ecological processes with social values in a spatial framework, this thesis demonstrates the potential of combining Earth observation, modelling, and local knowledge to support evidence-based decision-making. The proposed approach contributes to improved conservation prioritisation, stakeholder engagement, and sustainable water governance in mountain regions, while supporting progress toward international sustainability agendas, including the Sustainable Development Goals related to water, climate, and ecosystems.

Key words: Freshwater ecosystem services, water quality, Central Andes, headwater streams, remote sensing, governance of aquatic resources

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To my family

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Abstract

High-altitude lakes and headwater streams of the Andes provide essential ecosystem services, including drinking water supply, agricultural support, flood regulation, carbon storage, and cultural benefits for local communities. Despite their importance, these freshwater systems remain poorly monitored and vulnerable, and are increasingly affected by climate change, land use change, water extraction, and other human pressures. This thesis investigates how environmental change and human activities influence water quality and freshwater ecosystem services in the Central Andes of Bolivia. Through five complementary studies, it develops an integrated framework that combines Earth observation, field measurements, modelling, and social perception surveys to better understand freshwater ecosystems as coupled social-ecological systems, shaped by human actions.

At the largest scale, the research provides the first continent-wide characterisation and classification of Andean lakes, identifying distinct “lake districts” with shared climatic, topographic, and hydrological features. This regional perspective reveals strong gaps in monitoring and long-term data, especially in the Central Andes, and highlights how uneven knowledge can limit effective water management. A complementary synthesis of ecological studies identifies the main threats facing Andean lakes, including ultraviolet radiation, climate-driven changes in temperature and salinity, nutrient enrichment, invasive species, mining, and increasing pressure from human activities.

Zooming in to the watershed scale, the thesis examines how anthropogenic land use/land cover and water allocation affect stream water quality in small Andean catchments. The results show the importance of natural covers on stream-banks, and that human alteration of water flows, through irrigation and diversions, can obscure natural signals such as dilution and nutrient retention, complicating water quality assessment. These findings demonstrate why management strategies must account for both landscape structure and hydrological modification, rather than treating water quality as a purely natural process.

At the scale of individual lakes, satellite data and field measurements are used to assess trophic state and carbon dynamics, offering new insights into how organic matter and nutrients behave in small high-altitude lakes. These indicators help reveal early signs of ecological change that are difficult to detect through traditional monitoring alone.

Crucially, the research also incorporates how local communities perceive freshwater ecosystem services. Surveys show that people value water not only for practical uses such as drinking or irrigation, but also for cultural identity, well-being, and fairness in access. Integrating these social values with biophysical indicators allows ecosystem services to be assessed more realistically and transparently, revealing trade-offs and priorities that matter for decision-making.

Overall, this thesis demonstrates that integrating Earth observation, field science, modelling, and local knowledge provides a powerful framework for assessing freshwater ecosystem services in data-limited mountain regions. By linking ecological indicators of water quality with human perceptions, hydroclimatic variables, and landscape drivers across scales, the research advances understanding of Andean freshwater systems and highlights key factors influencing their sustainability. The framework supports more informed and inclusive decision-making for water management, conservation prioritisation, and stakeholder engagement, and offers a scalable approach that can be applied to other mountain regions facing similar environmental and governance challenges.

Populärvetenskaplig sammanfattning

Högalpina sjöar och källflöden i Anderna tillhandahåller viktiga ekosystemtjänster, inklusive dricksvattenförsörjning, vatten till jordbruk och boskapsskötsel, översvämningsreglering, kollagring samt kulturella värden för lokala samhällen. Trots deras betydelse är dessa sötvattenssystem fortfarande bristfälligt övervakade och sårbara, och påverkas i allt större utsträckning av klimatförändringar, förändrad markanvändning, vattenuttag och andra påfrestningar orsakade av människan. Denna avhandling undersöker hur miljöförändringar och mänskliga aktiviteter påverkar vattenkvaliteten och de sötvattensbaserade ekosystemtjänsterna i Centrala Anderna i Bolivia. Genom fem kompletterande studier utvecklas ett integrerat ramverk som kombinerar satellitobservationer, fältmätningar, modellering och undersökningar av lokala invånares uppfattningar för att bättre förstå sötvattens ekosystem som sammankopplade social-ekologiska system formade av mänskliga handlingar.

På den större skalan presenterar forskningen den första kontinentövergripande karakteriseringen och klassificeringen av Andernas sjöar, där distinkta "sjödistrikt" identifieras utifrån gemensamma klimatologiska, topografiska och hydrologiska egenskaper. Detta regionala perspektiv synliggör betydande brister i övervakning och långsiktiga data, särskilt i centrala Anderna, och visar hur ojämn kunskap kan begränsa en effektiv vattenförvaltning. En kompletterande syntes av ekologiska studier identifierar de huvudsakliga hoten mot andinska sjöar, inklusive ultraviolett strålning, klimatdrivna förändringar i temperatur och salthalt, näringsbelastning, invasiva arter, gruvverksamhet samt ökande påverkan från mänskliga aktiviteter.

Genom att zooma in till avrinningsområdesnivå analyserar avhandlingen hur antropogen markanvändning / marktäckning och vattenallokering påverkar vattenkvaliteten i vattendrag i små avrinningsområden i Anderna. Resultaten visar betydelsen av naturlig vegetation längs vattendragens stränder och att mänsklig omfördelning av vattenflöden, genom bevattning och avledningar, kan dölja naturliga signaler såsom utspädning och näringsretention, vilket försvårar

bedömningen av vattenkvalitet. Resultaten understryker varför förvaltningsstrategier måste ta hänsyn till både landskapsstruktur och hydrologisk modifiering, snarare än att betrakta vattenkvalitet som en enbart naturlig process.

På nivån av enskilda sjöar används satellitdata och fältmätningar för att bedöma trofiskt tillstånd och koldynamik, vilket ger nya insikter i hur organiskt material och näringsämnen beter sig i små höghöjdssjöar. Dessa indikatorer bidrar till att upptäcka tidiga tecken på ekologiska förändringar som är svåra att identifiera enbart genom traditionell miljöövervakning.

Avgörande är att forskningen också integrerar hur lokala samhällen uppfattar sötvattnets ekosystemtjänster. Enkäterna visar att människor värdesätter vatten inte enbart för praktiska användningar som dricksvatten och bevattning, utan även för kulturell identitet, välbefinnande och rättvisa i tillgången till vatten. Genom att integrera dessa sociala värden med biofysiska indikatorer kan ekosystemtjänster bedömas på ett mer realistiskt och transparent sätt, vilket synliggör de avvägningar och prioriteringar som är centrala för beslutsfattande.

Sammanfattningsvis visar denna avhandling att integrering av jordobservationsdata, fältstudier, modellering och lokal kunskap ger ett kraftfullt ramverk för att bedöma sötvattensbaserade ekosystemtjänster i databristpräglade bergsregioner. Genom att koppla ekologiska indikatorer för vattenkvalitet till hydroklimatiska variabler, människors uppfattningar, och landskapsdrivna faktorer över flera skalor bidrar forskningen till en fördjupad förståelse av Andernas sötvattenssystem och identifierar centrala faktorer som påverkar deras hållbarhet. Ramverket stödjer mer informerat och inkluderande beslutsfattande för vattenförvaltning, prioritering av naturvårdsinsatser och engagemang av intressenter, och erbjuder en skalbar metod som kan tillämpas i andra bergsregioner som står inför liknande miljömässiga och styrningsrelaterade utmaningar.

Resumen divulgativo

Los lagos de alta montaña y los arroyos de cabecera de los Andes proporcionan servicios ecosistémicos esenciales, incluyendo el suministro de agua potable, el apoyo a la agricultura y la ganadería, la regulación de inundaciones, el almacenamiento de carbono y beneficios culturales para las comunidades locales. A pesar de su importancia, estos sistemas de aguas continentales vulnerables son poco monitoreados, y se ven cada vez más afectados por el cambio climático, el cambio de uso del suelo, la extracción de agua y otras presiones humanas. Esta tesis investiga cómo los cambios ambientales y las actividades humanas influyen en la calidad del agua y en los servicios ecosistémicos de aguas continentales en los Andes Centrales de Bolivia. A través de cinco estudios complementarios, se ha desarrollado un marco integrado que combina datos de imágenes de satélite,

mediciones de campo, modelización y encuestas sobre la percepción social para comprender mejor los ecosistemas de aguas continentales como sistemas socioecológicos acoplados, moldeados por las acciones humanas.

En una escala continental, la investigación presenta la primera caracterización y clasificación de los lagos andinos, identificando distintos “distritos lacustres” con características climáticas, topográficas e hidrológicas compartidas. Esta perspectiva regional revela importantes vacíos en el monitoreo y en los datos de largo plazo, especialmente en los Andes Centrales, y pone de manifiesto cómo el conocimiento desigual limita una gestión eficaz del agua. De forma complementaria, una síntesis de estudios ecológicos identifica las principales amenazas que enfrentan los lagos andinos, entre ellas la radiación ultravioleta, los cambios impulsados por el clima en la temperatura y la salinidad, el incremento de nutrientes, especies invasoras, actividades mineras y el incremento de las presiones antrópicas.

Al enfocarse en la escala de cuenca, esta tesis analiza cómo el uso y la cobertura del suelo, junto con la forma en que se distribuye y se usa el agua, influyen en la calidad del agua de los arroyos en pequeñas cuencas andinas. Los resultados destacan la importancia de conservar la vegetación natural en las riberas y muestran que las alteraciones humanas de los caudales, a través del riego y las derivaciones, pueden interferir procesos naturales como la dilución y la retención de nutrientes, dificultando la evaluación real de la calidad del agua. Estos hallazgos demuestran que las estrategias de gestión deben considerar tanto la estructura del paisaje como las modificaciones hidrológicas, en lugar de tratar la calidad del agua como un proceso exclusivamente natural.

En la escala de lagos individuales, se emplean datos satelitales y mediciones de campo para evaluar los niveles del estado trófico y la dinámica del carbono, aportando nuevos conocimientos sobre el comportamiento de la producción primaria, materia orgánica y los nutrientes en pequeños lagos de alta montaña. Estos indicadores permiten detectar señales tempranas de cambio ecológico que resultan difíciles de identificar únicamente mediante programas de monitoreo tradicionales.

Un aspecto clave de esta investigación es que incorpora la manera en que las comunidades locales perciben los servicios ecosistémicos asociados a los cuerpos de aguas continentales. Las encuestas muestran que las personas valoran los recursos hídricos no solo por sus usos prácticos, como el consumo o el riego, sino también por su importancia para la identidad cultural, el bienestar y la equidad en el acceso. Integrar estos valores sociales con indicadores biofísicos permite evaluar los servicios ecosistémicos de manera más realista y transparente, haciendo visibles los compromisos, prioridades y tensiones que son fundamentales para la toma de decisiones.

En conjunto, esta tesis demuestra que la integración de observación de la Tierra, trabajo de campo, modelización y conocimiento local proporciona un marco sólido para evaluar los servicios ecosistémicos de aguas continentales en regiones

montañosas con escasez de datos. Al vincular indicadores ecológicos de la calidad del agua con las percepciones humanas y los factores del paisaje a diferentes escalas, la investigación contribuye a una mejor comprensión de los sistemas de aguas continentales andinos y destaca los factores clave que influyen en su sostenibilidad. El esquema de trabajo propuesto apoya una toma de decisiones evidenciada e inclusiva para la gestión del agua, la priorización de la conservación y la participación de los actores sociales, y ofrece un enfoque escalable que puede aplicarse a otras regiones montañosas que enfrentan desafíos ambientales y de gobernanza similares.

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Papers

List of appended papers

- I. **Prado, P.E.**, Modenutti, B., Aranguren-Riaño, N., Balseiro, E., Samanez, I., Campero, M., Fernández, C.E., Rivera-Rondon, C.A., Carvajal-Vallejos, F.M., López-Paría, D., Herrera-Martínez, Y., de los Ríos-Escalante, P. & Steinitz-Kannan, M. 2024. “*Andean Lakes: a proposal for lake districts*”, *Inland Waters*. DOI: 10.1080/20442041.2024.2379147
- II. Campero, M., Balseiro, E., Fernández, C.E., Modenutti, B., **Prado, P.E.**, Rivera-Rondon, C.A., Carvajal-Vallejos, F.M., Herrera-Martínez, Y., López-Paría, D.M., Aranguren-Riaño, N., Samanez, I., de los Ríos-Escalante, P.R. & Steinitz-Kannan, M. 2025. “*Andean lakes: endangered by natural and anthropogenic threats*”, *Inland Waters*. DOI: 10.1080/20442041.2024.2395157
- III. **Prado, P.E.**, Oporto, C., Jönsson, K., Rejas, D., Martinez, V., Persson, K. 2025. “*Influence of land use/land cover on stream water quality in two watersheds in the Central Andes of Bolivia: An optimised methodology*”, *Ecological Indicators*. DOI: 10.1016/j.ecolind.2025.113984
- IV. **Prado, P.E.**, Rejas, D., Oporto, C., Jönsson, K., Murphy, K., Persson, K. 2026. “*Unveiling Small High Andean Lakes: A Multi-Sensor Framework for Monitoring Trophic State, Dissolved Organic Carbon, and Hydroclimatic Drivers in Central Andes of Bolivia*”. (submitted to journal).

- V. **Prado, P.E.**, Rejas, D., Oporto, C., Jönsson, B. Decsi, K., Persson, K. 2026. *“Freshwater Ecosystem Services valuation in a Region of the Central Andes of Bolivia: a novel framework”*. (submitted to journal).

Author’s contributions to the appended papers

- I. The first author (PEP) was responsible for the collection of geographical data and formal analysis, plotted the GIS maps, provided all the tabular (including those used in the maps) and the graphical results. PEP also coordinated the writing of the section on Central Andes. The second and fourth author supervised the writing of the manuscript. The third author coordinated the working meetings.
- II. PEP was responsible for the collection and analysis of geographical data and produced maps and tabular results. PEP contributed equally in the literature review. The second and fourth author supervised the writing of the manuscript. The first and the third author coordinated the working meetings.
- III. PEP was the lead and corresponding author. The second author supervised the writing of the manuscript. PEP planned and conducted most of the field research, processed the laboratory results, performed the geographical and statistical analyses, and prepared the initial and revised drafts, including all sections and illustrations. All authors contributed by discussing the results and revising the drafts.
- IV. PEP was the lead and corresponding author. The second author supervised the manuscript preparation. PEP and the second author designed and conducted the fieldwork, and performed most of the laboratory analyses; the fifth author also contributed to the laboratory analyses. PEP processed the laboratory data, carried out the geographical and statistical analyses, and prepared the initial and revised drafts of the manuscript, including all sections and illustrations. All authors contributed to the interpretation of the results and critically revised the manuscript drafts.
- V. PEP formulated the scope and conceptualised the study, planned and coordinated the field survey, curated the database, and conducted the visualisation, geographical and statistical analyses. PEP and the fifth author wrote the manuscript, and all authors contributed by discussing the results and revising the drafts.

Other Publications and Conference Presentations

Book chapters

- De los Ríos-Escalante, P.R., Esse, C., Correa-Araneda, F., Rodríguez, L., Fernández, C.E. & **Prado, P.E.** 2024. “*Potential effects of climate change in saline shallow lakes in the north of Chile (Salar de Atacama, 23°S, Chile) and South Lipez of Bolivia (Khalina Lake, 22.61°S)*”. In: Singh, A.L., Jamal, S. & Ahmad, W.S. (eds) *Climate Change, Vulnerabilities and Adaptation*. Springer, Cham. DOI: 10.1007/978-3-031-49642-4_9

Peer-reviewed journal

- Fernández, C.E., Campero, M., Acosta, F., **Prado, P.E.**, Maldonado, M., Goitia, E., Stamou, G., Michaloudi, E. & López, C. 2024. “*Diversity of Rotifera in freshwaters of Bolivia: an updated checklist*”, *Diversity*, 16, 589. DOI: 10.3390/d16090589

Conference Presentations

- **Prado, P.E.**, Oporto, C., Jönsson, K., Rejas, D., Martinez, V., Maraño, M., Persson, K. 2023. “Spatial temporal changes in water quality of an urban / sub-urban / rural watershed influenced by land use”. 9th IWA-ASPIRE Conference & Exhibition 2023. International Water Association (IWA), Taiwan – Kaohsiung. Abstract No. 311.
- **Prado, P.E.**, Rejas, D., Jönsson, K., Campero, M., Fernandez, C.E., Oporto, C., Martinez, V., Maraño, M., Persson, K. 2023. “Estimation of CDOM and Chlorophyll-a in high Andean Small Lakes using Landsat satellite data”. 9th IWA-ASPIRE Conference & Exhibition 2023. International Water Association (IWA), Taiwan – Kaohsiung. Abstract No. 309.

- **Prado, P.E.**, Modenutti, B., Aranguren-Riaño, N., Balseiro, E., Samanez, I., Campero, M., Fernández, C.E., Rivera-Rondon, C.A., Carvajal-Vallejos, F.M., López-Paría, D., Herrera-Martínez, Y., de los Ríos-Escalante, P. & Steinitz-Kannan, M. 2024. “Andean Lakes: a proposal for lake districts”. 37th Congress of the International Society of Limnology. SIL 2024, Brazil - Foz de Iguaçu. Abstract No. 1409.

Abbreviations

AC	Atmospheric correction
AI	Artificial intelligence
AOP	Apparent optical properties
ARIES	ARtificial Intelligence for Environment & Sustainability
CDOM	Chromophoric dissolved organic matter
CHELSA	Climatologies at High Resolution for the Earth's Land Surface Areas
CHIRPS	Climate Hazards Center InfraRed Precipitation with Station Data
Chl- <i>a</i>	Chlorophyll- <i>a</i>
CIESIN	Centre for Integrated Earth System Information
CISES	Common International Classification of Ecosystem Services
CS	Carbon storage
DEM	Digital elevation model
DOC	Dissolved organic carbon
ES	Ecosystem service(s)
EO	Earth observation
ET	Evapotranspiration
FAO-56	Food and Agriculture Organization Irrigation and Drainage Paper No. 56
GEE	Google Earth Engine
GIS	Geographical information system
GS	Google scholar
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
InVEST	Integrated Valuation of Ecosystem Services and Trade-Offs
IOP	Inherent optical properties
IPCC	Intergovernmental Panel on Climate Change
LULC	Land use/land cover

MCDA	Multi-criteria decision analysis
MEA	Millennium Ecosystem Assessment
ML	Machine learning
NCI	Normalised chlorophyll index
NCP	Nature's contributions to people
NDCI	Normalised difference chlorophyll index
NDR	Nutrient delivery ratio
NDVI	Normalised difference vegetation index
NDWI	Normalised difference water index
NPS	Non-point source
NRCS	Natural Resources Conservation Service
OAC	Optically active components
PCA	Principal components analysis
PLSR	Partial least square regression
RF	Random forest
ROC-AUC	Area under the receiver operating characteristic curve
<i>Rrs</i>	Remote sensing reflectance
RS	Remote sensing
SDR	Sediment delivery ratio
SENAMHI	Servicio nacional de meteorología e hidrología
SES	Social-ecological system
SHAL	Small high Andean lakes
SHAP	Shapley Additive exPlanations
SHG	Soil hydrologic groups
SNAP	Sentinel Application Platform
SOLVES	Social Values for Ecosystem Services
SRTM	Shuttle Radar Topography Mission
STS	Social-technological system
SWAT	Soil & Water Assessment Tool

TEEB	The Economics of Ecosystems and Biodiversity
TR55	Technical Release 55, "Urban Hydrology for Small Watersheds"
TSI	Trophic state index
TWI	Topographic wetness index
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States geological survey
UVR	Ultraviolet radiation
VIP	Variable importance in projection
WQ	Water quality
WQI	Water quality index
WSY	Water seasonal yield
XGB	Extreme gradient boosting

1 Introduction

Ecosystem Services (ES) are essential processes and conditions within natural ecosystems that sustain human life and well-being (G. Daily, 1997). These services represent the dynamic interactions between society and ecosystems functions (Balvanera et al., 2006; Kremen, 2005; Sekercioglu et al., 2010). The groundbreaking concept of ES, minted in the 80's, became a foundational element in the emergent field of ecological economics. It was conceived to bridge the gap between two distinct scientific communities: ecosystem ecology on one side, and environmental and resource economics on the other (Costanza et al., 2017).

Despite their significance, ES are often undervalued or overlooked in decision-making, even as they play a critical role in addressing global challenges such as climate change, biodiversity loss, and water scarcity. Research on ES is crucial to advancing our understanding of the complex interdependencies between ecosystems and human societies. Such knowledge is indispensable for developing strategies to mitigate environmental degradation and promote sustainable development. Research on ES in Latin America has rapidly developed, demonstrating an increasing trend, both in the number of articles (Castro-Díaz et al., 2022) and in research outputs of integrated studies since 2000s (Balvanera et al., 2012; Perevochtchikova et al., 2019). However, the most frequently mentioned countries in the studies were Mexico, Brazil, Costa Rica, Chile and Colombia (Aguirre et al., 2023; Perevochtchikova et al., 2019), while Bolivia has been scarcely treated in the ES research.

In Latin America, the case of freshwaters is an example where ES would be valuable yet is scarcely used. ES related to water quality (WQ) are crucial for sustainable development because they support the health of people and natural ecosystems. These are delivered through watersheds, shaped by the landscape hydrology, and need to be managed through integrated water resources management and governance. There is important scientific evidence that headwaters provide crucial ES (Asmare et al., 2024; Baattrup-Pedersen et al., 2018; Bieroza et al., 2024). There are more than one thousand watersheds of these types along Central Andes, and millions of people depend on these water resources. Despite some existing studies, research on the ES provided by high Andean streams and small lakes remains limited and insufficiently explored, such as the influence of landscape features in stream WQ, the trophic state dynamics of small lakes, and carbon

cycling. This information concerning the ecosystems' functioning is then critical for the further valuation of the corresponding ES.

Global databases and Earth Observation (EO) has been widely recognised in scientific literature as a comprehensive data source for monitoring and assessing ecosystem functions in diverse types of environments (Cord et al., 2017; Ustin & Middleton, 2021; Zhao et al., 2022). In addition, the Goggle Earth Engine (Funk et al., 2015) is a powerful platform for accessing, analysing and visualising huge amounts of EO data. However, the validation of global and EO-derived information with available ground-based data is essential to ensure the reliability of the assessments. Ground-truthing not only enhances the accuracy of remote sensing (RS) products and inventories but also supports the identification of meaningful indicators that can be used for robust predictions and informed environmental decision-making.

Formal management and decision-making processes, related to water resources and land use planning, frequently fail to systematically incorporate stakeholders' perspectives and local communities' perceptions (Alamanos et al., 2022; Castro-Díaz et al., 2022; Ebner et al., 2022). This oversight can lead to mismatches between policy objectives and local priorities, reducing the effectiveness and legitimacy of environmental interventions. For this reason, this thesis integrates perception analysis into the valuation criteria of freshwater ES, which is essential (Alvarado-Arias et al., 2023). Such integration serves as a local tuning or scaling factor that enhances the contextual relevance of ES assessments, ensuring that valuation frameworks reflect not only biophysical and economic dimensions but also the social and cultural values attributed to ecosystems by the people who depend on them. Consequently, this approach promotes more inclusive, equitable, and adaptive management strategies aligned with both ecological sustainability and community well-being.

The aim of this thesis is to develop a social-ecological knowledge integration framework that links global databases, RS-based WQ indicators, machine learning (ML) modelling, and field data with socio-economic perceptions, to support freshwater ES valuation and evidence-based decision-making for integrated sustainable water governance.

The objectives were:

1. Characterise the diversity, distribution, and typology of Andean lakes and synthesise the major environmental and anthropogenic threats affecting their ecological integrity and ecosystem services (Papers I and II)
2. Quantify and analyse the influence of land use/land cover on stream water quality in two human-impacted Central Andean watersheds (Paper III).
3. Assess the trophic state, dissolved organic matter and dissolved organic carbon dynamics on small high Andean lakes (Paper IV).

4. Integrate a plural valuation of freshwater ecosystem services in high-altitude Andean watersheds by combining socio-economic perceptions with spatially explicit biophysical models and ML analyses (Paper V).

1.1 Summary of appended papers

Paper I addresses a critical knowledge gap by systematically characterising the distribution and diversity of Andean lakes, the headwaters crucial for South American water resources. Novelty lies in the first comprehensive grouping analysis of >5000 lakes, integrating morphometry, geological origin, climate, and limnological information to delineate 11 lake districts across the North, Central, and South Andes. Findings reveal that over 60% of lake surface area is concentrated in nine large lakes, while most lakes are <1 km², and highlight notable gaps and asymmetries in available data, with limited limnological measurements and scarce long-term studies. This framework supports integrated water resource management in climate-sensitive, socioeconomically diverse Andean regions.

Paper II presents a review synthesising over 700 ecological studies to identify major threats to Andean lakes, highlighting their vulnerability despite Ramsar protection. Key stressors include UVR, climate-driven changes in water balance, eutrophication, invasive species, and mining, with emerging pressures from lithium extraction in salt flats. These impacts compromise biodiversity, ecosystem functioning, and services such as water provision, fisheries, and tourism, while posing potential human health risks. Many lakes remain unexplored, and limnological data are scarce, particularly in regions facing increasing anthropogenic pressure. The study emphasises the urgent need for multi-scale research and proactive management to safeguard these unique freshwater ecosystems.

Paper III addressed a key gap in Andean watershed research by quantifying how LULC influences stream WQ across seasons and spatial scales in the Bolivian central Andes, a region characterised by steep gradients and anthropogenic pressures on water resources. Novelty lies in the integration of multi-sensor satellite data with field data and cumulative upstream effects to assess scale-dependent LULC-WQ relationships. The development of an Anthropogenic Land Cover Index (ALCI) provides a transferable, simplified proxy for WQ prediction. Results highlight the buffering role of natural LULC types and the importance of multiscale approaches for hydrological ES quantification.

Paper IV fills a critical data and monitoring gap for small high Andean lakes (SHAL) by integrating multi-satellite RS with targeted field measurements to assess WQ and hydrological dynamics in remote Bolivian central Andean catchments. An additional novelty is the systematic comparison of freely available multispectral

imagery using multiple atmospheric correction (AC) methods, the application of optimised ML regression models, and explicit uncertainty estimation for key WQ parameters. Incorporating landscape and hydroclimatic descriptors significantly improved model performance, particularly for organic matter dynamics and trophic state linked to WQ and hydrologic ES. This approach offers a scalable, cost-effective framework for operational WQ monitoring and ecosystem-based management in data-scarce high-altitude regions.

Paper V presents an integrative valuation of freshwater ES in high-altitude Andean lakes, streams, and wetlands (*bofedales*) by combining socio economic, environmental, and biophysical data. It links survey based perceptions, binary willingness to pay indicators, use-based importance metrics, and willingness to participate measures with spatial outputs from InVEST models (water yield, nutrient and sediment delivery, carbon storage) and key geographical variables such as distance to water bodies, slope, topographic wetness index (TWI), elevation, and population density. ML approaches with hyperparameter tuning, feature importance, and SHAP analyses are applied to identify key drivers of ES valuation. The framework explicitly distinguishes instrumental (monetary and use-based) from relational (identity, heritage, and participation-based) values, enabling a pluralistic, spatially explicit assessment that addresses key gaps in freshwater ES valuation, particularly for regulating and cultural services.

1.2 Thesis structure

As shown in Figure 1, the dissertation is structured based on four main papers (Papers I, III-V) and an additional one (Paper II) as a supplementary for Paper I. Papers I and II served to characterise the Andes cordillera, from the limnological perspective, and provide a literature review on the natural and anthropogenic treats for Andean lakes. This was also useful to detect information gaps and asymmetries. Papers III and IV focused on cost-effective techniques for estimating WQ in streams and SHAL located in headwaters for local study cases in the Central Andes. Paper V integrates some results of Papers III and IV with biophysical ES modelling outputs, and the analysis of social perception in the study area for ES valuation.

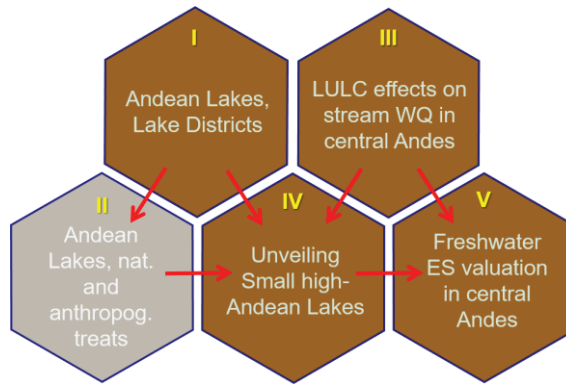


Figure 1. Graphical abstract of the thesis structure

2 Theoretical background

This research adopts a transdisciplinary social-ecological systems (SES) approach grounded in complex systems thinking, critical realism, and sustainability science, integrating EO, ML, biophysical indicators, and socio-cultural valuation to co-produce actionable knowledge for water governance. The purpose of this theoretical background is to contextualise this research within an integrated knowledge-building framework and to provide the conceptual foundations necessary for its integration.

2.1 Social-ecological system

Complex interactions of humans and nature systems are shaping landscape continuously as coupling and co-evolutionary processes (Folke et al., 2016; Walker & Salt, 2006). The knowledge construction and technology advancement is an indissoluble part of those social-ecological processes, with their particularities along territories, development and with increasing influence of globalisation (Chaves-Chaparro et al., 2025; Schorr et al., 2021). Knowledge flows and transfers are complex also and present some challenges specially for developing countries, where inequalities exist in terms of human well-being and ecosystem fragility, and with limited access to technical-scientific tools and information (Boampong et al., 2024; Schorr et al., 2021). Critical investigation of the reality, both biophysical and social structures, is relevant to understand the relationships between freshwater ecosystems and people. In this research, these models of the reality were intended to interpret patterns and findings with the aim to fill knowledge gaps and inform decision-making or policy-design, desirably towards conservation, adaptation and transformation (Clark, 2007; National Academies of Sciences, 2021; O'Brien, 2012). Thus, this study is conceptually situated in the core of sustainability science and aligned with safe and just operating space for action, based on planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) as biophysical ceiling, and social development as foundation (O'Neill et al., 2018; Raworth, 2017), respectively.

2.1.1 Complex system thinking and hydro-landscape interface co-evolution

Freshwater systems exemplify complex adaptive systems in which biophysical, ecological, and social processes interact across multiple spatial and temporal scales. Complex systems thinking provides a conceptual foundation for understanding such systems by emphasising non-linearity, feedbacks, uncertainties, emergent properties, path dependency, and threshold behaviour (Hjorth & Bagheri, 2006; Walker & Salt, 2006). In hydrology, this perspective challenges reductionist approaches that isolate individual processes and instead promotes an integrated view of catchments as evolving social-ecological systems (Falkenmark & Folke, 2002; Sivapalan et al., 2012). Rivers, lakes, wetlands, glaciers, soils, and groundwater are not merely connected through physical flows of water, matter and energy, but through dynamic interactions shaped by climate variability, geomorphology, ecosystems, and human activities. In this research, the term hydro-landscape interface (hydro-landscape) refers to the spatially explicit zone where hydrological processes, landscape structure, ecological functioning, and human activities co-evolve.

Within this paradigm, the concept of hydro-landscape co-evolution has gained prominence. Co-evolution refers to the reciprocal and long-term feedbacks between hydrological processes, ecological dynamics, and human systems, whereby changes in one domain modify the trajectories of the others (Blöschl, 2013; Sivapalan et al., 2012). Hydro-landscapes are thus not static configurations but historically contingent outcomes of coupled natural and social processes. This perspective is central to the “Panta Rhei” decade of the International Association of Hydrological Sciences, which explicitly framed hydrology as the science of water systems under change, recognising humans as endogenous components of the hydrological cycle (Kreibich et al., 2025; Montanari et al., 2013; Sivapalan & Blöschl, 2015).

The relevance of complex system thinking becomes particularly evident when considering the unresolved problems of hydrology identified by Blöschl et al. (2019). Among the 23 unsolved problems, several directly relate to the challenges of understanding freshwater systems in high-altitude environments: predicting hydrological change under non-stationary climate conditions, identifying dominant processes across scales, understanding emergent behaviour in coupled human-water systems, and quantifying the resilience and tipping points of hydrological systems. High Andean freshwater systems embody these challenges acutely, as they are subject to strong climatic gradients, cryospheric influences, and increasing anthropogenic pressures, while remaining comparatively underrepresented in global hydrological research.

High Andean lakes and streams form interconnected networks that regulate water availability, biogeochemical cycling, and ecological integrity in mountain regions. These systems are typically characterised by high solar radiation, strong seasonality, and tight coupling between terrestrial and aquatic processes. Small headwater

streams and lakes play a crucial role in controlling downstream WQ and quantity, acting as sinks or transformers of nutrients, organic matter, and sediments (Alexander et al., 2007; P. D. Brown et al., 2008). However, their dynamics are highly sensitive to changes in temperature, precipitation patterns, glacier retreat, and LULC change. Alterations in one component of the hydro-landscape, such as shifts in lake stratification, changes in inflow regimes, or modifications of riparian zones, can propagate through the system, producing non-linear and sometimes unexpected outcomes for ecosystems and human water use.

Despite their importance, significant knowledge gaps persist regarding the co-evolutionary dynamics of high-altitude freshwater systems. Many hydrological and ecological models remain limited to represent feedbacks between lakes, streams, catchment processes, and human interventions at relevant scales (Blöschl, 2013; Sivapalan et al., 2012). Moreover, long-term observational data are scarce, limiting the ability to detect thresholds, regime shifts, or legacy effects (Carpenter et al., 2011; Cauvy-Fraunié & Dangles, 2019). This constrains our understanding of how high Andean hydro-landscapes respond to compound pressures such as climate change, mining, agriculture, and infrastructure development, and how these responses affect water-related ES critical for downstream communities.

Recognising freshwater systems as co-evolving complex systems thus reframes the problem from one of prediction alone to one of understanding processes, interactions, and system trajectories (Hjorth & Madani, 2014). This shift opens space for integrating social dimensions, institutional arrangements, and technological interventions as intrinsic components of hydrological dynamics. Such an integrated perspective sets the stage for the next subsection, which examines how social-technological systems and critical realism provide a strong theoretical foundation for understanding how WQ knowledge is generated, validated, and applied, and how human and ecological processes interact within evolving hydro-landscapes.

Adopting a holistic watershed perspective emphasises the interactions among lakes, streams, wetlands, highlighting the landscape variables, such as slope, LULC, and hydroclimatic variables, that most influence system dynamics and WQ (Sivapalan et al., 2012; Tezel et al., 2025). In high Andean ecosystems, the coupling of small headwater lakes and streams regulates nutrient cycling and ecological integrity. Monitoring key WQ variables, such as physicochemical parameters, chlorophyll-a (Chl-a), water transparency, CDOM and DOC, is essential for assessing the provisioning of freshwater ES (Brönmark & Hansson, 2017; P. D. Brown et al., 2008; Cauvy-Fraunié & Dangles, 2019; Naderian et al., 2024).

2.1.2 Social-technological systems and critical realism

This section conceptualises RS, geospatial data infrastructures, and data-driven modelling as components of a broader social-technological system (STS) through which knowledge of WQ is produced, validated, and mobilised. While STS

emphasises the technical and organisational dimensions of knowledge production, SES approaches explicitly integrate human and ecological dynamics, highlighting feedbacks between natural processes and human decision-making. Grounded in a critical realist perspective (Archer et al., 1998; Bhaskar, 1975, 1979), the section distinguishes between observable empirical patterns (e.g., satellite retrievals, modelled relationships), the actual processes that generate them (e.g., biogeochemical, hydrological, and land-water interactions), and the underlying causal mechanisms shaped by both natural dynamics and human activities. Within this framework, the following subsections progressively introduce (i) the physical basis of RS of WQ (observation of natural processes); and (ii) RS reflectance (linking optical signals to ecosystem dynamics); (iii) key optically active constituents governing inland water optical properties (biophysical mediators of energy and nutrient flows); (iv) LULC and catchment-scale controls on stream WQ (human drivers influencing WQ); (v) the derivation of spatially explicit LULC metrics from EO data (spatially explicit indicators of land-water interactions); (vi) the role of global databases and climate products in hydrological and WQ analysis (knowledge integration across scales); and (vii) the emergence of Python-based ML and artificial intelligence (AI) as a paradigm shift in environmental modelling (analytical capacity to model complex SES interactions).

Together, these elements illustrate the complementarity of empirical observation, data-driven modelling, and socio-environmental context, reinforcing the value of integrating diverse data sources, multi-layered technological and computational tools, scientific and field knowledge to understand and manage freshwater ecosystem processes.

2.1.2.1 Remote sensing of water quality

RS enables the acquisition of information about objects without direct physical contact and has a long history of application in natural resource studies, as it provides reliable information over large areas with high accuracy and reasonable costs. Its use has been fundamental for cartography, resource interpretation, land use planning, and ecological studies. The application of RS techniques to the detection and prediction of physicochemical parameters in freshwater bodies began in the 1980s (Blöschl et al., 2019). A seminal contribution was made by Lillesand et al. (1983), who developed predictive models for water transparency, Chl-*a*, total phosphorus, turbidity, total nitrogen, and the Trophic State Index (TSI) for 60 lakes. Since then, numerous studies have expanded these approaches (Table 1).

Table 1. Web of Science search results showing the number of studies on water quality retrieved from satellite data in the literature.		
Search phrase	Years	Number of results
(river* OR lake* OR reservoir*) AND ("water quality" OR "water pollution" OR "optical water quality") AND ("remote sensing" OR satellite* OR Landsat OR Sentinel)	1983 - 2025	4443

Spectral reflectance, also referred to as spectral reflectance irradiance or irradiance ratio, is defined as the proportion of incident light (or other electromagnetic radiation) that is reflected by a surface. In aquatic environments, however, reflectance must explicitly account for the portion of light that originates from beneath the water surface, as the signal recorded by remote sensors is strongly influenced by subsurface optical processes.

The total radiance (L_t) measured by an airborne or satellite sensor is composed of four main components:

$$L_t = L_p + L_s + L_v + L_b \quad (1)$$

where L_p corresponds to atmospheric path radiance, L_s to surface-reflected radiance, L_v to subsurface volumetric radiance emerging from the water column, and L_b to bottom-reflected radiance (Jensen, 2014). Water bodies receive irradiance from both direct solar radiation and diffuse sky radiation and the interaction of this incoming energy with the atmosphere and the aquatic medium determines the final signal detected by the sensor.

A clear distinction must be made at this point, between apparent optical properties (AOP) and inherent optical properties (IOP), as this conceptual separation underpins the interpretation of remotely sensed aquatic signals. IOP are the absorption and scattering characteristics of water and its constituents that depend solely on the concentration and composition of optically active components (OAC) within the medium, independent of the ambient light field (IOCCG, 2006; Kirk, 2011; Preisendorfer, 1958, 1971, 1976; Preisendorfer & Tyler, 1958). These include the spectral absorption coefficient, scattering coefficient, and backscattering properties, which provide a material description of how light interacts with the water column. In contrast, AOP, such as RS reflectance (R_{rs}) and the diffuse attenuation coefficient (K_d), depend not only on the optical characteristics of the water column but also on the ambient light field, including solar geometry, atmospheric conditions, and viewing configuration (Casey et al., 2020). While satellite sensors directly observe AOP such as R_{rs} , the ultimate objective in bio-optical RS applications is often to infer IOP or constituent concentrations from these measurements using radiative transfer models, empirical relationships, semi-analytical algorithms or other complex models. This distinction is fundamental for understanding the physical basis and limitations of WQ retrievals and for ensuring conceptual consistency when linking RS observations to biogeochemical and ecological processes.

2.1.2.2 Remote sensing reflectance (R_{rs})

When the goal is to retrieve information on organic and inorganic constituents within the water column, such as suspended sediments or Chl-*a*, it is necessary to extract the subsurface volumetric radiance (L_v), which carries information on OAC

(Jensen, 2014). This process leads to the estimation of Rrs for water surfaces, defined as the ratio between the water-leaving spectral radiance and the downwelling spectral irradiance incident on the water surface.

$$Rrs(\theta, \varphi, \lambda) \doteq \frac{L_w(\theta, \varphi, \lambda)}{E_d(\lambda)} \quad (2)$$

In this formulation, θ and φ describe the polar and azimuthal viewing directions, respectively, and λ represents wavelength. $L_w(\theta, \varphi, \lambda)$ is the spectral radiance exiting the water in a given direction, originating from subsurface light that has been transmitted upward through the air-water interface, while $E_d(\lambda)$ is the downwelling spectral irradiance at the water surface. Measurements associated with Rrs are typically obtained above the water surface across wavelengths ranging from the near-ultraviolet to the near-infrared (approximately 350-800 nm; Mobley, 1999).

Rrs cannot be measured directly and must be estimated using methods that remove sky-reflected radiance from the water surface. The surface reflectance factor (ρ) is not an IOP of water, as it depends on sky conditions, wind speed, solar zenith angle, and viewing geometry. Inaccurate estimation of ρ can introduce significant errors in Rrs , particularly under high wind speeds or near-zenith solar positions, where sun-glint effects become pronounced (Mobley, 1999).

In practice, Rrs can be derived by estimating L_w and E_d using radiative transfer models such as *HydroLight* (Mobley, 1994; Mobley, 2020), which simulates light propagation in aquatic environments. This approach requires input parameters including image acquisition date and location, solar zenith angle, cloud cover, and wind speed, typically obtained from image metadata or local and national climate datasets (J. Chen et al., 2017). Several tools have been developed to operationalise these processes known as atmospheric correction (AC) methods in aquatic RS, each relying on different assumptions, radiative transfer strategies, sensor specificity, and computational requirements. In this research, three widely used AC processors, C2RCC, iCOR, and ACOLITE, were applied to Sentinel-2 and Landsat 8&9 imagery.

ACOLITE performs AC using a dark spectrum fitting approach with optional exponential extrapolation and supports multiple multispectral sensors (Vanhellemont, 2020; Vanhellemont & Ruddick, 2021). C2RCC implements a coupled water-atmosphere radiative transfer framework to retrieve water-leaving reflectance (ESA & Brockmann et al., 2016; Caballero & Stumpf, 2020), while iCOR applies a physically based atmospheric and adjacency correction scheme optimised for both land and inland waters (VITO & De Keukelaere et al., 2018). In parallel, standard Level-2 surface reflectance products generated by Sen2Cor for Sentinel-2 (Main-Knorn et al., 2017) and LaSRC for Landsat 8&9 (Vermote et al., 2018) were included for comparison. Alternative tools include GLAM BioLith-RT, designed for radiative transfer modelling in complex waters (Schiassi et al., 2019), as well as Polymer, QUAC, OC-SMART, and the SeaDAS L2GEN processor.

These and many other AC methods, some requiring commercial licenses, ancillary data, or substantial computational resources, have been comprehensively described and evaluated in several review studies (IOCCG, 2010; Mobley et al., 2016; Pahlevan et al., 2021; Warren et al., 2019).

Although R_{rs} is sensitive to changes in illumination geometry and atmospheric conditions, even when concentrations of total suspended solids, Chl-*a*, and CDOM remain constant (Mishra & Mishra, 2012), it constitutes the fundamental quantity from which water colour products are derived, including phytoplankton Chl-*a* concentration and inherent optical properties (Pahlevan et al., 2017).

2.1.2.3 Key optically active components for inland water quality

Studies integrating GIS and RS for inland water monitoring are fundamentally based on the analysis of OAC, primarily phytoplankton or algal biomass, suspended solids, and CDOM. These constituents govern water colour through wavelength-dependent absorption and scattering processes that shape the spectral reflectance signal emerging from the water column (Kirk, 2011). Optical sensors capture this reflected radiation, enabling the spatially explicit estimation of WQ indicators such as Chl-*a*, turbidity, transparency, and CDOM (Jensen, 2014).

Among these, algal density, closely associated with Chl-*a* concentration, is a key proxy for eutrophication and trophic state (Carlson, 1977; Kirk, 2011). Eutrophication represents a successional process driven by nutrient enrichment, particularly nitrogen and phosphorus, leading to enhanced primary productivity and recurrent phytoplankton blooms (Wetzel, 1983). While eutrophication can occur naturally, anthropogenic nutrient inputs currently dominate this process, often resulting in altered food webs, reduced biodiversity, and harmful cyanobacterial blooms. Suspended solids further influence aquatic optics by increasing turbidity through enhanced scattering and absorption, thereby reducing light penetration and limiting photosynthesis (Gholizadeh et al., 2016).

Chl-*a* exhibits distinct spectral features that enable its estimation through spectral indices derived from multispectral satellite data. However, retrieval accuracy decreases in optically complex waters where multiple OACs coexist, such as lakes, rivers, and coastal systems (Z. Yang et al., 2017). Small and shallow lakes remain particularly underrepresented in the literature, and turbid waters continue to pose methodological challenges (Ambrose-Igho et al., 2021; Cheng et al., 2013). Numerous indices and band ratios have been evaluated for Chl-*a* estimation (Abdelal et al., 2022; Gholizadeh et al., 2016; Oliveira Santos et al., 2023; Tran et al., 2023), with the Normalised Chlorophyll Index (NCI) demonstrating robust performance across diverse datasets, especially in turbid environments without requiring additional spectral bands (Cheng et al., 2013). Similarly, the Normalised Difference Chlorophyll Index (NDCI) has shown strong potential across multiple sensors and water types for detecting algal blooms and estimating Chl-*a* concentration ranges (Beck et al., 2016; Mishra & Mishra, 2012).

Recent advances in satellite missions have significantly improved inland water monitoring capabilities. Sentinel-2 and Landsat-8 data have proven effective for estimating Chl-*a*, turbidity, suspended matter, and Secchi depth in small and moderately turbid lakes using regression, band-ratio, and hyperspectral validation approaches (Abdelal et al., 2022; Ambrose-Igho et al., 2021). ML techniques, including decision trees, support vector regression and extreme learning machines, have further enhanced retrieval accuracy when validated against long-term monitoring databases (Arias-Rodriguez et al., 2021; Xu et al., 2019). Long-term satellite records also enable the analysis of seasonal and interannual variability in surface water temperature, turbidity, and Chl-*a*, although some overestimation may occur during peak productivity periods (Huovinen et al., 2019). Nutrient concentrations, particularly total phosphorus, are often inferred indirectly via relationships with Chl-*a* and suspended matter (Xiong et al., 2019). Multiplatform and multisensor frameworks combining satellite, airborne, and unmanned aerial vehicles data enhance monitoring of small reservoirs, while cloud-based platforms such as Google Earth Engine (GEE) enable large-scale, efficient Chl-*a* prediction (Castro et al., 2020; Ouma et al., 2020; L. Wang et al., 2020).

CDOM represents another critical OAC, consisting of a complex mixture of humic and fulvic substances derived largely from terrestrial organic matter. It imparts yellow to brown colouration to inland waters and strongly absorbs radiation in the blue and ultraviolet regions (Boyle et al., 2009; Kirk, 2011). CDOM concentrations vary in response to hydrological processes, climate, LULC, and watershed characteristics, including urban and agricultural inputs (Fuentes-Rivas et al., 2015). Although dissolved organic carbon (DOC) cannot be directly retrieved by RS due to its optically inactive fraction, strong regional relationships between CDOM absorption and DOC concentration have been widely reported, enabling CDOM to serve as an effective proxy, particularly in forested and wetland-dominated catchments (Griffin et al., 2018; Massicotte et al., 2017).

Advances in EO have substantially improved the retrieval of CDOM from satellite data. RS-based CDOM estimation has been validated across multiple sensors, with enhanced performance achieved through the use of *Rrs*, expanded spectral ranges, and the application of inversion techniques and ML algorithms (Blix et al., 2018; J. Chen et al., 2017; Zhu et al., 2014). These developments underscore the growing capacity of satellite observations to support integrated, multi-parameter assessments of inland WQ across broad spatial and temporal scales.

Beyond its optical relevance, CDOM plays a fundamental ecological role by regulating underwater light climate and mediating exposure to ultraviolet radiation (UVR). Zooplankton are particularly sensitive to UVR, which can induce lethal and sublethal effects that reduce grazing efficiency and alter trophic interactions (Fernández & Rejas, 2017). This mechanism is especially important in high-altitude tropical lakes, where incident UVR levels are naturally elevated. Although UVR was once considered of limited ecological significance due to its rapid attenuation in surface waters (Kirk, 2011), climate change has increased interest in this factor,

and subsequent studies have shown that UVR can penetrate several meters in optically clear systems, increasing its ecological relevance (Zagarese et al., 1998). In this context, CDOM acts as a key photoprotective agent, with higher concentrations enhancing UV attenuation and buffering aquatic biota from radiation stress.

Despite the widespread application of GIS and RS in WQ assessment, there is ongoing debate regarding the effects of climate change on DOM export from terrestrial to aquatic systems. Rising temperatures (Freeman et al., 2001), together with climate- and land use-driven alterations in hydrological balance (Evans et al., 2002), are expected to influence DOM mobilisation and delivery to aquatic systems. Andean soils are particularly rich in organic matter of vegetal origin, promoting the export of humic and fulvic compounds and contributing to the naturally high CDOM concentrations observed in many high-altitude lakes. However, shifts in temperature regimes or soil moisture conditions may disrupt this balance, with potential consequences for trophic structure and WQ. In this context, RS-based CDOM estimates provide a valuable integrative indicator of terrestrial-aquatic carbon linkages and offer a powerful means to assess ecosystem responses to climate change in vulnerable mountain regions.

2.1.2.4 Land use/land cover and catchment controls on stream water quality

LULC patterns are widely recognised as dominant controls on stream and river WQ, reflecting the cumulative effects of human activities within a watershed. Intensified agriculture, industrial expansion, and rapid urbanisation alter hydrological pathways and biogeochemical processes, increasing nutrient loads, suspended sediments, organic matter, and contaminants delivered to aquatic systems (Giri & Long, 2014; Pratt & Chang, 2012; Shi et al., 2017; Z. Zhang et al., 2021). Consequently, monitoring and interpreting WQ through the lens of catchment characteristics has become essential for protecting ecosystem integrity and public health (S. Li et al., 2022; F. Zhang et al., 2022).

LULC influences WQ primarily through non-point source (NPS) pollution mechanisms, whereby diffuse runoff mobilises nutrients, sediments, and pollutants from soils and impervious surfaces into stream networks (L. Chen et al., 2008; H. Gao et al., 2018; Lee et al., 2009). Seasonal precipitation patterns and hydrological variability further regulate flow conditions and contaminant concentrations, often producing strong temporal contrasts between wet and dry periods (Vega et al., 1998). As a result, WQ represents an integrated response to LULC, climate, soils, and topography operating across multiple spatial and temporal scales.

Since the 1970s, numerous studies have documented relationships between watershed LULC composition and stream water chemistry across North America, Europe, and Asia (Allan, 2004b, 2004a; Locke, 2024b; Mashala et al., 2023; Rimer et al., 1978). These studies consistently show that agricultural and urban land uses are associated with elevated nutrient concentrations, turbidity, and altered ionic composition, while forested and natural areas tend to exert protective effects by

promoting infiltration, nutrient retention, and sediment stabilisation. However, such analyses remain limited in the Andean region of South America and are largely absent in Bolivia, despite the region's high watershed density, strong environmental gradients, and increasing anthropogenic pressures (Baltodano et al., 2022; Gossweiler et al., 2019, 2021; Linke et al., 2019).

A key conceptual advance in LULC-WQ research is the recognition that scale matters. Relationships between LULC and WQ differ depending on whether LULC metrics are quantified at the entire catchment scale, along stream reaches, or within riparian buffer zones (Allan, 2004b; Locke, 2024a). Catchment-scale metrics capture cumulative upstream influences, while reach-scale and riparian buffers better represent near-stream processes such as bank erosion, shading, nutrient uptake, and direct pollutant interception. Empirical evidence suggests that riparian LULC often exerts a disproportionate influence on nutrients and suspended solids, whereas broader catchment characteristics may better explain long-term or baseflow-driven WQ patterns.

Methodologically, studies have employed a wide range of GIS-based approaches, including correlation and regression analyses linking LULC metrics to WQ variables, hydrological modelling of NPS pollution (McBroom et al., 2008; A. Wang et al., 2020; Wesström et al., 2014), and scenario-based assessments of land use change impacts (Liu et al., 2016; Randhir & Tsvetkova, 2011). Nevertheless, current understanding remains constrained by coarse-resolution LULC data, scale mismatches between predictors and response variables, environmental heterogeneity, and inconsistencies in statistical and modelling approaches (Locke, 2024a).

In regions that are highly vulnerable to climate change and rapid land use transformation, such as Bolivia, ecosystem-based and multiscale-scale approaches provide a promising framework for integrating land use planning, conservation, and WQ management (Ai et al., 2015; Prado et al., 2025; Shi et al., 2017). Strengthening the empirical linkage between LULC patterns, multi-scale processes, and stream WQ is therefore critical for supporting ES modelling, sustainable watershed management and advancing water-related Sustainable Development Goals.

2.1.2.5 Remote sensing derived LULC metrics

RS-derived LULC metrics have become central to understanding the spatial variability of stream and lake WQ, particularly in data-scarce regions and complex landscapes. Anthropogenic activities reflected in LULC patterns strongly influence WQ by interacting with natural watershed characteristics such as topography, climate, and hydrological connectivity (Ai et al., 2015; J. Wu & Lu, 2021). As a result, spatial heterogeneity in WQ often mirrors the distribution, intensity, and configuration of LULC across catchments and along river networks (F. Zhang et al., 2022).

Advances in EO have enabled the derivation of spatially explicit LULC datasets at resolutions suitable for watershed-scale and sub-catchment analyses. Numerous

studies have demonstrated the effectiveness of RS-based LULC classification for linking landscape composition to WQ indicators, especially where official geographic databases are incomplete or unavailable (Asmare et al., 2024; Baltodano et al., 2022; Bu et al., 2014; Gossweiler et al., 2021; Locke, 2024b). These approaches allow consistent characterisation of both urban and rural landscapes and facilitate the analysis of land-water interactions across multiple spatial scales, including riparian corridors, stream reaches, and entire catchments (Morin et al., 2022).

Multisensor satellite systems provide complementary information that enhances LULC discrimination and the extraction of environmentally relevant metrics. Optical sensors such as Sentinel-2 and Landsat-8&9 capture spectral variability associated with vegetation, soil moisture, impervious surfaces, and water bodies, enabling the calculation of indices such as the Normalised Difference Vegetation Index (NDVI; Rouse et al., 1974; Tucker, 1979) and Normalised Difference Water Index (NDWI; B.-C. Gao, 1996; McFeeters, 1996) that are directly linked to ecohydrological processes (Mirmazloumi et al., 2022). Thermal data from Landsat-8&9 further support the differentiation of LULC types along elevation and climatic gradients through land surface temperature patterns, which are particularly informative in mountainous watersheds. Synthetic aperture radar (SAR) data, such as Sentinel-1, contribute topographic and moisture-sensitive information that improves the representation of terrain controls, especially in riparian zones and steep landscapes where optical signals may be limited.

The integration of these multisource datasets within cloud-based platforms such as GEE has significantly advanced large-scale LULC-WQ analyses by enabling harmonised processing, spatial alignment, and efficient handling of long-term time series (Abdali et al., 2024; Capolupo et al., 2020; Greifeneder et al., 2021; Shelestov et al., 2017). Such frameworks support the derivation of detailed LULC metrics, such as proportional area, fragmentation, and proximity to water, that can be statistically linked to observed patterns in nutrients, turbidity, organic matter, and thermal regimes.

By explicitly coupling RS-derived LULC information with WQ observations, these approaches provide a powerful basis for ES assessment and watershed-scale management, enabling the identification of critical source areas and land use configurations that disproportionately affect aquatic ecosystem functioning.

2.1.2.6 Global databases and products for hydrological and WQ Analysis

The increasing availability of global datasets, including RS-based and climate products, has substantially enhanced the capacity to analyse hydrological processes and WQ dynamics across multiple spatial and temporal scales. These products provide consistent, spatially explicit information on climatic drivers, landscape characteristics, and anthropogenic pressures, which are essential for understanding watershed functioning, particularly in data-scarce regions.

Precipitation is a primary driver of runoff generation, erosion, and NPS pollution. Satellite–gauge blended products such as the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) offer high-resolution (~5 km) precipitation estimates with strong performance in mountainous and semi-arid regions, making them widely used in hydrological and WQ studies (Funk et al., 2015). Complementary long-term climatologies, including CHELSA and WorldClim (Fick & Hijmans, 2017; Karger et al., 2021), provide monthly precipitation and temperature surfaces that support the characterisation of hydroclimatic gradients and seasonal variability.

Evapotranspiration (ET) products derived from RS, such as MOD16 and SSEBop (Running et al., 2021; Senay et al., 2023), as well as CHELSA-based reference evapotranspiration (ET₀), are critical for assessing water balance, catchment water stress, and ecosystem productivity (Trabucco & Zomer, 2022; Zomer et al., 2007, 2008, 2022). These datasets enable the integration of atmospheric demand into hydrological models and WQ assessments, particularly in regions where ground-based measurements are sparse.

Hydrographic and geomorphological datasets, including HydroSHEDS and LakeATLAS, provide standardised representations of river networks, catchment boundaries, and lake morphometry at global scales, facilitating cross-basin comparisons and spatially consistent analyses of hydrological connectivity, including more than 50 variables on hydrology, physiography, climate, LULC, soil, geology and anthropogenic (Lehner et al., 2022). Soil-related products, such as global soil hydraulic properties and soil hydrologic groups, support the evaluation of infiltration capacity, runoff potential, and sediment transport processes (Ross et al., 2018; Simons et al., 2020).

Additional global datasets further enrich watershed analyses. Gridded population products (GPWv4) serve as proxies for human pressure (CIESIN, 2018; SEDAC, 2023) especially in national or continental scales, while rainfall erosivity and soil erodibility indices enable the assessment of erosion risk and sediment delivery to streams (Das et al., 2024; Panagos et al., 2017, 2023). Nutrient and sediment export datasets derived from synthesis studies provide valuable baseline information for regional-scale WQ assessments (Hamel & Guswa, 2015; Mandle & others, 2024). Together, these global products support integrated, multi-driver analyses of hydrological and WQ processes and strengthen the linkage between climate, LULC, and aquatic ecosystem responses.

Across the diverse global datasets and RS products described above, cloud-based platforms have become essential for their effective integration and analysis. GEE the most widely used, exemplifies a socio-technical computational paradigm that combines open-access satellite archives, geospatial programming, cloud computing, rapid processing, visualisation, and collaborative knowledge production (Gorelick et al., 2017). Beyond its technical capacity, GEE integrates multiple layers of knowledge, including sensor physics, geospatial analytics, domain expertise, and user-contributed algorithms, facilitating knowledge transfer and co-construction

through a global research community increasingly supported by artificial intelligence tools. This paradigm enables scalable, reproducible, and multi-decadal hydrological and WQ analyses, supporting transparent workflows, rapid visualisation, and the integration of multi-sensor datasets across spatial and temporal scales.

2.1.2.7 Python, ML, and AI for hydrological and WQ Analysis

Although Python was introduced in the early 1990s, it only became a mainstream language for ML after 2010 and achieved dominance in ML research after 2015. The widespread adoption of Python-based ML and artificial intelligence (AI) frameworks represents a complementary socio-technological paradigm shift in environmental modelling. This paradigm is characterised by open-source ecosystems, collaborative development, algorithmic transparency, and the capacity to model complex, nonlinear relationships across heterogeneous data sources (Pedregosa et al., 2011; Reichstein et al., 2019; Van Rossum & Drake, 2009). Together, these attributes have fundamentally transformed how hydrological, WQ, and ES processes are analysed, interpreted, and communicated.

Python has become the dominant language for scientific computing and data-driven environmental research due to its modular architecture, extensive libraries (e.g., NumPy, SciPy, scikit-learn, XGBoost), and seamless interoperability with geospatial, statistical, and visualisation tools (McKinney, 2010; Pedregosa et al., 2011). Beyond technical efficiency, Python enables reproducible research practices through script-based workflows, version control, and community-driven validation, reinforcing transparency and cumulative knowledge production (Wilson et al., 2014). This open computational culture aligns closely with the socio-technical paradigm introduced by cloud platforms, extending it from data access to advanced modelling and inference.

ML methods are particularly well suited for complex social-ecological systems, where processes are often nonlinear, multiscale, and driven by interactions among biophysical, climatic, and anthropogenic factors (Hsieh, 2009; Olden et al., 2008). In hydrology and WQ research, ML has proven effective for pattern discovery, prediction, and variable importance assessment when traditional parametric models are constrained by assumptions of linearity, stationarity, or data normality (Nearing et al., 2021; C. Shen, 2018). Algorithms such as k-means clustering, random forests (RF), partial least squares regression (PLSR), and gradient boosting machines have become standard tools for exploring spatial heterogeneity, identifying dominant controls, and predicting responses across large environmental datasets.

Unsupervised learning approaches, including k-means clustering, facilitate the classification of lakes, rivers, or catchments into functional or typological groups based on multivariate environmental similarity, enabling regionalisation and comparative analysis across thousands of systems (Jain, 2010; MacQueen, 1967). Supervised learning methods such as RF are widely applied for LULC classification, WQ prediction, and hydroclimatic impact assessment due to their

robustness to multicollinearity, capacity to handle high-dimensional data, and strong predictive performance (Belgiu & Drăgu, 2016; Breiman, 2001).

In regression contexts, ensemble tree-based models and latent-variable approaches such as PLSR allow the integration of satellite reflectance, catchment descriptors, and hydroclimatic variables to predict WQ indicators including Chl-*a*, turbidity, transparency, and CDOM, among others (Fan et al., 2016; Mutanga et al., 2012; Wold et al., 2001). When combined with rigorous hyperparameter tuning, cross-validation, and feature importance analysis, these models provide both predictive accuracy and process-level insight into land-water and climate-water interactions (Molnar, 2022). Feature importance metrics, permutation importance, and variance-based indicators help disentangle dominant drivers while accounting for interaction effects and nonlinear responses.

More recently, explainable AI methods have addressed a longstanding critique of ML models as “black boxes”. Techniques such as SHapley Additive exPlanations (SHAP) provide theoretically grounded, locally consistent interpretations of model predictions, enabling the attribution of outcomes to individual variables across environmental and socio-economic contexts (Lundberg & Lee, 2017). This is particularly relevant in coupled human-natural systems, where interpretability is essential for policy relevance, stakeholder engagement, and ES valuation.

In socio-environmental research, gradient boosting classifiers and related AI models have been increasingly applied to integrate survey data, spatial indicators, environmental variables, and ES model outputs to explain instrumental, relational, and socio-cultural values (C. Shen, 2018; H. Shen et al., 2019; Willcock et al., 2018). These approaches allow the explicit handling of class imbalance, nonlinear decision boundaries, and complex interactions between social preferences and biophysical conditions, thereby strengthening the empirical basis for sustainability science and environmental decision-making.

Recent advances in deep learning, advanced neural networks, and generative artificial intelligence offer promising future opportunities for WQ analysis and RS research, particularly in the context of large time series and long-term monitoring datasets. Deep learning architectures such as convolutional neural networks (CNNs), recurrent neural networks (RNNs), long short-term memory (LSTM) models, and transformers have demonstrated strong potential for capturing complex, nonlinear relationships between spectral signals, environmental drivers, and *in situ* WQ parameters (Baek et al., 2020; Taheri Dehkordi et al., 2026; Tan et al., 2022). These methods are especially well suited for multi-sensor data integration, gap filling, anomaly detection, and the analysis of high-dimensional satellite time series spanning decades. Broader reviews of AI in WQ evaluation confirm that artificial neural networks and recurrent models enhance prediction and monitoring capabilities by learning directly from large and heterogeneous datasets, reducing reliance on manually derived empirical relationships (Rana et al., 2023; Y. Zhang et al., 2023). Furthermore, the integration of AI with RS enables automated detection and forecasting of water contamination dynamics at scales and temporal

frequencies unattainable with conventional methods, have opened new possibilities for data augmentation, uncertainty characterisation, and the reconstruction of missing or noisy observations in long-term monitoring records (Pang et al., 2025; L. Yang et al., 2025; Yun et al., 2024). As satellite archives continue to expand and WQ assessments increasingly rely on continuous, multi-scale observations, these data-driven approaches are expected to complement physically based models, enhancing predictive capability, scalability, and the extraction of previously underexplored patterns in aquatic systems.

Importantly, this Python-ML-AI paradigm is not merely technical. It constitutes a socio-technological system in which algorithms, data, domain expertise, and collective intelligence co-evolve through global user communities, open repositories, and continuous methodological innovation (Reichstein et al., 2019). When integrated with cloud-based platforms such as GEE, this paradigm enables end-to-end workflows, from data acquisition and preprocessing to modelling, interpretation, and visualisation, supporting scalable, reproducible, and interdisciplinary environmental research across spatial and temporal scales.

2.1.3 Sustainability science, planetary boundaries and social foundation

Sustainability science emerges as a transdisciplinary field explicitly concerned with understanding and governing the interactions between social and ecological systems under conditions of complexity, uncertainty, and non-linearity (Bettencourt & Kaur, 2011; Clark & Harley, 2020). Building on complex systems thinking (Section 2.1.1) and social-technological systems informed by critical realism (Section 2.1.2), sustainability science provides an integrative framework to analyse how human societies can persist, adapt, and transform while remaining within biophysical limits and meeting fundamental human needs. Rather than focusing solely on equilibrium or optimisation, sustainability science emphasises co-evolution, feedbacks, thresholds, and normative questions related to desirable futures (Clark & Harley, 2020; Kates et al., 2001).

A central contribution of sustainability science is the articulation of global environmental limits through the Planetary Boundaries framework. Originally proposed by Rockström et al. (2009) and later refined by Steffen et al. (2015), this framework identifies a set of critical Earth system processes, such as climate change, freshwater use, biogeochemical flows, and biosphere integrity, within which humanity can operate safely. Transgressing these boundaries increases the risk of abrupt or irreversible environmental change. From a social-ecological systems perspective, planetary boundaries can be understood as emergent macro-scale constraints arising from cumulative interactions between localised human activities and Earth system dynamics. They highlight that hydrological systems, biogeochemical cycles, and ecosystems are not infinitely resilient, reinforcing the need to analyse water, land, and ecosystem processes as interconnected and scale-dependent components of the hydro-landscape.

Complementing the biophysical focus of planetary boundaries, the concept of a social foundation addresses the normative and ethical dimensions of sustainability. Popularized through Raworth's "Doughnut Economics" framework (Raworth, 2012, 2017), the social foundation defines a set of minimum social thresholds necessary to ensure human well-being, equity, and dignity. These include access to water, food, health, education, energy, and participation, among others. The social foundation emphasises that sustainability is not only about avoiding environmental collapse but also about preventing social deprivation. In social-ecological terms, it foregrounds distributional issues, power relations, and institutional arrangements that mediate how ecosystem benefits and risks are shared across societies (Berkes et al., 2003; Ostrom, 2009).

The integration of planetary boundaries and the social foundation creates a conceptual "safe and just operating space" for humanity, where ecological integrity and social well-being are jointly considered (Raworth, 2017; Rockström et al., 2009). This integration is particularly relevant for water systems, which simultaneously function as biophysical regulators (e.g., nutrient cycling, climate feedbacks) and as critical providers of ES essential for human societies (Falkenmark & Rockström, 2006; Vörösmarty et al., 2010). From a critical realist perspective, planetary boundaries and social foundations can be interpreted as operating at different ontological levels: biophysical constraints emerge from underlying natural mechanisms, while social thresholds reflect historically contingent social structures, values, and power relations. Their interaction shapes observable outcomes such as WQ degradation, ES loss, or social conflict over resources.

This subsection serves as a conceptual bridge toward Section 2.2 on ES. While sustainability science, planetary boundaries, and the social foundation define the broad normative and systemic context of sustainability, the ES framework operationalises these ideas by focusing on the mechanisms through which ecosystems contribute to human well-being. ES provide the analytical link between ecological processes and social benefits, enabling the assessment of trade-offs, synergies, and governance options within social-ecological systems. In this sense, ES can be understood as the functional interface through which societies navigate the safe and just operating space defined by sustainability science.

2.2 Ecosystem services or Nature's Contributions to People (NCP)

The ES concept emerged from ecological economics as an integrative framework to articulate the multiple ways in which ecosystems sustain human life and well-being, while simultaneously addressing the long-standing separation between ecological and economic systems (Braat & de Groot, 2012; Costanza et al., 1997; G. Daily, 1997). Early contributions in ecological economics highlighted the biophysical

limits of economic growth, concerns regarding resource depletion, and the dependence of human development on ecological processes, thereby laying the foundations for a systematic consideration of nature's contributions to society (Costanza et al., 1997; Ehrlich & Mooney, 1983).

Since its formal introduction, the ES framework has evolved into a central conceptual and policy-relevant approach for linking biophysical processes, human well-being, and decision-making (G. C. Daily et al., 2009). Major international initiatives, including the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010), and subsequent classification and accounting systems (Haines-Young & Potschin, 2018), have progressively institutionalised ES within environmental governance, planning, and sustainability assessment (Braat & de Groot, 2012; S. Wu et al., 2024). More recently, the Nature's Contributions to People - NCP, (Díaz et al., 2018; Intergovernmental Platform on Biodiversity and Ecosystem Services, 2018) framework has expanded this perspective by emphasising plural values, diverse knowledge systems, and non-economic dimensions of human-nature relationships (Hill et al., 2021).

In this thesis, freshwater ES are understood as contributions from freshwater ecosystems to human life and well-being, and are used as an analytical bridge between biophysical WQ dynamics, social perceptions, and institutional decision-making. The following subsections elaborate on the conceptual role of ES/NCP in linking ecology and society, incorporating human needs and values, and supporting knowledge co-production within a transdisciplinary sustainability framework.

2.2.1 Bridges: biophysics and society, ecology and economy

Within SES and STS perspectives, ES works as a conceptual bridge linking biophysical processes, technological tools, social well-being, and economic decision-making. ES intend to provide a common language through which ecological change can be translated into socially meaningful and policy-relevant terms, while remaining grounded in ecological functioning. In this sense, ES operate as boundary concepts that connect natural sciences, social sciences, and governance arenas, enabling interdisciplinary analysis and transdisciplinary engagement. Following subsections familiarise with (i) the historical roots of ecological economics; (ii) discuss the need for unified ES classifications and taxonomies; (iii) and examine key normative debates surrounding weak and strong sustainability and the commodification of nature.

2.2.1.1 Historical roots of ecological economics

Foundational studies of ecological economics emerged from concerns regarding Earth's overpopulation, environmental degradation, resource limits, and development trajectories (Ehrlich, 1971; Ehrlich et al., 1977; Sachs, 1977). These

concerns were accompanied by early critiques of economic growth and conventional welfare metrics (Cole et al., 1973; Daly, 1977; Mishan, 1967; Nordhaus, 1973, 1977; Nordhaus & Tobin, 1972), as well as by bio-economic perspectives emphasising thermodynamic constraints and material throughput (Georgescu-Roegen, 1975; Passet, 1979; Van Dieren, 1979). Parallel discussions addressed the question of how nature sustains human life and well-being, including early attempts to assess the value of nature's services (Westman, 1977).

At this point of conceptual inflection, the term *ecosystem service* was formally introduced by Ehrlich & Ehrlich (1981) framing ecosystems as providers of life-support functions essential to human societies. Subsequent research expanded these ideas through discussions of extinction, substitution, and ES (Mooney, 1983), as well as through the influential *Our Common Future* report (World Commission on Environment and Development, 1987), which linked environmental limits to intergenerational equity and sustainable development. Further contributions emphasised the pursuit of the common good (Daly & Cobb, 1989), and proposed environmental functions as a unifying concept between ecology and economics (De Groot, 1987).

The foundational study of ES of Costanza et al. (1997), which presented a global valuation of ES, together with *Nature's services* book (G. C. Daily, 1997), marked a decisive moment in the consolidation of ES as a research field. These works provided an explicit interdisciplinary foundation for bridging economy and ecology, later described by Costanza as contributing to the 'science and management of sustainability' (Costanza et al., 2017; Martínez-Alier & Muradian, 2015).

An important institutional and interdisciplinary milestone was the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), which established ES as a global policy framework linking ecosystems to human well-being. The Economics of Ecosystems and Biodiversity (TEEB, 2010) further advanced this agenda by translating ES into decision-relevant economic information. The Common International Classification of ES (CICES, Haines-Young & Potschin-Young, 2018) subsequently provided a standardised classification system to support consistent mapping, accounting and comparison across studies. More recently, the Intergovernmental Science-Policy Platform on Biodiversity and ES (IPBES, 2018) broadened the conceptual scope through the Nature's Contributions to People (NCP) framework, explicitly recognising plural values and diverse knowledge systems. Finally, the System of Environmental-Economic Accounting-Ecosystem Accounting (SEEA-EA, United Nations, 2021) operationalised ES within official environmental-economic accounting, embedding these concepts into national policy and planning.

2.2.1.2 Unifying ecosystem services classification and taxonomy

As ES research expanded across disciplines and policy domains, multiple classification systems and terminologies emerged, reflecting different epistemological positions, objectives, and application contexts. While this plurality

has supported methodological innovation, it has also generated conceptual fragmentation, inconsistencies, and challenges for comparison, synthesis, and policy uptake. In response, considerable effort has been devoted to developing unifying classification frameworks and shared taxonomies capable of bridging ecological, economic, and social perspectives.

Widely used ES classifications, including those developed within the MEA, CICES, and IPBES/NCP, differ in their structuring principles, treatment of ecological processes, and representation of human values. These differences have practical implications for ES mapping, indicator selection, valuation approaches, and decision support. Recent synthesis efforts, including the work of Affinito et al. (2025), emphasise the need for coherent taxonomic structures that explicitly link ecosystem functions, services, benefits, and values, while remaining flexible enough to accommodate diverse socio-ecological contexts.

However, several gaps remain, ranging from practical to conceptual. These include the loss of information and mismatches between different classification systems (Brander et al., 2024; La Notte et al., 2017), the absence of a common scientific and transdisciplinary taxonomy, and persistent difficulties in integrating academic, practitioner, stakeholder, local, and policy-oriented knowledge systems. Such gaps complicate efforts to translate biophysical indicators into socially meaningful ES and to compare results across regions and scales.

In this context, the development of integrative frameworks, potentially supported by comparative tables linking ES classes, ecological functions, indicators, and reference frameworks, can enhance transparency, interoperability, and analytical consistency. Such approaches are particularly relevant for freshwater systems, where biophysical processes, human uses, and institutional arrangements are tightly coupled and highly context-dependent.

2.2.1.3 Weak vs strong sustainability and commodification critique

After more than four decades of conceptual and empirical development, ES research has increasingly differentiated into distinct normative and analytical clusters, most notably those associated with weak and strong sustainability paradigms (Bonnedahl et al., 2022; Dietz & Neumayer, 2007). Weak sustainability perspectives typically assume a high degree of substitutability between natural and human-made capital, often supporting monetary-market valuation approaches and integration into conventional economic decision-making. In contrast, strong sustainability emphasises critical natural capital, ecological thresholds, and the non-substitutability of key ecosystem functions, aligning more closely with resilience thinking and precautionary governance (Arrow et al., 2012; Dias et al., 2020; Ekins et al., 2003; Walker et al., 2004).

These debates are closely linked to broader critiques of the commodification of nature, which question the reduction of complex ecological relationships and plural human values to monetary-market metrics. Scholars such as Spash (2015, 2017, 2020) have argued that market-based valuation approaches risk obscuring ethical,

cultural, and relational dimensions of human-nature interactions, while reinforcing power asymmetries and technocratic decision-making. Within this critical tradition, ES are understood not merely as economic goods, but as socially constructed relationships embedded in specific cultural, institutional, and ecological contexts.

In sustainability science and SES research, these debates underscore the importance of plural valuation approaches that extend beyond pricing and explicitly recognise diverse value domains. This perspective provides a conceptual foundation for non-market, perception-based valuation methods and supports the integration of ES into transdisciplinary frameworks that prioritise ecological integrity, social justice, and long-term sustainability.

2.2.2 ES modelling, valuation, human needs, perceptions & behaviour

Building on the conceptual role of ES as a bridge between biophysical processes and societal well-being, this section examines how ES are modelled and valued, and how these processes relate to human needs, perceptions, and behaviour. While a wide range of analytical tools exists for ES modelling and valuation, increasing attention has been given to the incommensurability of values, the irreducibility of fundamental human needs, and the limitations of purely monetary approaches. Within this context, relational values and perception-based approaches have emerged as key concepts for capturing the ways in which people recognise, experience, and interact with ecosystems. The following subsections review (i) modelling frameworks for ES; (ii) theoretical perspectives on values and human needs, and the (iii) role of perceptions and relational values in ES assessment.

2.2.2.1 Tools and modelling frameworks for ES

The increasing demand for the assessment, quantification, mapping, and valuation of ES has driven the rapid development of conceptual frameworks, modelling approaches, and decision-support tools over the last two decades. This demand reflects a broader need to integrate ecological processes with socio-economic considerations in environmental planning and policy. A central challenge in ecosystem management lies in addressing trade-offs among multiple ES across heterogeneous landscapes, often under conditions of uncertainty and limited data availability.

Despite substantial progress, the literature consistently indicates that there is no single standardised method for mapping and valuing ES. Studies differ widely in their objectives, spatial scales, classifications of ES, and valuation techniques, which complicates comparison across case studies and reduces the transferability of results to policy contexts (Seppelt et al., 2012; Van Zanten et al., 2014). These methodological divergences reflect the inherent plurality of the ES concept but also reveal persistent gaps in achieving an integrated and operational framework for ES assessment.

Among the available approaches, InVEST focuses on scenario-based evaluation of ES trade-offs and has been extensively applied in land use planning contexts, including regions characterised by social and environmental conflicts (Rincón-Ruiz et al., 2019).

A broad range of models and tools has been developed to operationalise ES assessments. Widely used process-based and spatially explicit models include SWAT and ARIES, each representing different modelling philosophies. SWAT is particularly effective for hydrological and WQ-related services, while ARIES adopts a more dynamic, probabilistic approach grounded in artificial intelligence and semantic modelling of ES flows (Villa et al., 2014). While these tools have advanced the operationalisation of ES, their applicability is often constrained by data availability, scale mismatches, and uncertainties in model parameterisation.

Complementary to these models, indicator-based and hybrid approaches such as Weighted Provider Richness (WPR), Ecosystem Services Inequality (ESI), DPSIR frameworks, Cellular Automata-Markov Chain models, and participatory Multi-Criteria Decision Analysis (MCDA) have been applied to capture spatial dynamics, social equity dimensions, and land use change processes. Web-based platforms such as OPTamos (formerly NAIADE) and QUICKScan further facilitate interactive and participatory ES assessments, enabling scenario exploration and stakeholder engagement in decision-making processes.

SolVES (Social Values for Ecosystem Services) and MCDA provide flexible frameworks for assessing ES by integrating ecological, socio-cultural, and economic dimensions. SolVES, a GIS-based tool developed by the U.S. Geological Survey, quantifies and spatially maps social values of ES based on stakeholder preferences and environmental variables (Sherrouse et al., 2014; U.S. Geological Survey, 2020). MCDA complements this by structuring evaluations across multiple, often conflicting criteria, incorporating stakeholder weights and normative judgments, and enhancing transparency in decision-making, especially for ES that cannot be fully expressed in biophysical or monetary terms (Belton & Stewart, 2002; Chatzinikolaou et al., 2018).

Geospatial technologies play a central role in ES mapping and quantification. GIS and RS platforms, including ArcGIS, QGIS, IDRISI, ENVI, and increasingly cloud-based environments such as GEE, enable large-scale, repeatable ES assessments using land cover, climate, and topographic data. Long-term satellite-derived indices, particularly normalised indices (NDVI, NDCI, NDWI, among others), have been widely used as proxies for ecosystem productivity and land degradation since the early 1980s. These indicators are commonly linked to regulating and supporting services such as carbon sequestration, nutrient cycling, water infiltration, and erosion control (Canedoli et al., 2024).

However, reliance on productivity proxies such as vegetation indices introduces significant limitations. While remotely sensed indicators capture spatial and temporal patterns of vegetation dynamics, they fail to directly observe many underlying ecological processes, such as soil biogeochemistry, biodiversity

interactions, or WQ regulation. This limitation is particularly critical for emerging ES frameworks and valuation mechanisms, where uncertainty in ES supply can undermine credibility and trust.

Recent studies emphasise that global datasets, although valuable for large-scale assessments, may lead to substantial errors when applied at local or regional scales. In data-poor or remote regions, a hybrid strategy that integrates global datasets with targeted field measurements and local knowledge is increasingly recommended (Cerretelli et al., 2018). Moreover, combining supervised and unsupervised classification of high-resolution satellite imagery with *in situ* observations has proven essential for improving the reliability of ES maps, particularly in complex landscapes such as mountain and lake-dominated systems.

Despite the wide spectrum of ES quantification and valuation approaches and methodological advances, several key gaps remain. These include limited representation of ES interactions, disservices (negative nature's contributions) and trade-offs, acknowledge differences between ecosystem functions and services, differences in valuation approaches (from non-monetary to pricing) insufficient integration of uncertainty analysis, weak coupling between biophysical models and socio-economic valuation, and challenges in capturing temporal dynamics and non-linear ecosystem responses. Imbalances about ES studies (some ES are underrepresented), large biomes and crucial biomes are also underrepresented, in the case of central Andes of Bolivia, studies are almost absent. Addressing these gaps requires the development of integrative frameworks that combine RS, process-based modelling, participatory approaches, and decision-support frameworks, thereby strengthening the role of ES assessments in sustainable landscape management and policy design.

2.2.2.2 Theoretical perspectives on values and human needs

ES valuation has historically been dominated by economic approaches aimed at expressing ecosystem benefits in monetary terms to inform decision-making. However, ecological economics has long emphasised that many ecosystem values are incommensurable and cannot be meaningfully reduced to a single metric (Martínez-Alier & Muradian, 2015). Incommensurability arises because ES contribute to multiple dimensions of human well-being, biophysical, cultural, ethical, and social, that are governed by different value logics and cannot be fully compared or substituted.

This critique is closely linked to the distinction between weak and strong sustainability, as well as to broader debates on the commodification of nature. From a strong sustainability perspective, certain ecosystem functions and services constitute critical natural capital and are non-substitutable, rendering monetary valuation insufficient or even misleading. Consequently, valuation is increasingly understood not as pricing, but as a broader process of recognising, articulating, and deliberating values (Martínez-Alier & Muradian, 2015).

Within this plural valuation landscape, Max-Neef's Human Scale Development framework provides a foundational theoretical basis for understanding the relationship between ES and human well-being. Max Neef, 2016 (and earlier work) conceptualises human needs as finite, universal, and non-hierarchical, including subsistence, protection, affection, understanding, participation, leisure, creation, identity, and freedom. Crucially, while needs are universal, the satisfiers through which they are met are culturally and contextually specific. ES can thus be interpreted as potential satisfiers of multiple human needs, rather than as isolated economic goods.

This perspective challenges reductionist valuation approaches by emphasising that human needs are irreducible and multidimensional, and that well-being cannot be adequately captured through aggregate indicators or monetary metrics alone (Valenzuela & del Valle Barrera, 2023). In this thesis, this framework underpins the decision to adopt non-market valuation approaches that focus on social perceptions, recognition, and qualitative assessments of ES, particularly in relation to freshwater systems.

2.2.2.3 Perceptions, recognition and relational values

Recent advances in ES research have increasingly emphasised the importance of perceptions, recognition, and relational values in understanding human-nature interactions. Relational values refer to the meanings, responsibilities, identities, and social relationships that people associate with ecosystems, extending beyond instrumental (use-based) and intrinsic (nature-centred) value categories. This perspective aligns closely with the Nature's Contributions to People (NCP) framework, which explicitly recognises diverse worldviews and knowledge systems (Intergovernmental Platform on Biodiversity and Ecosystem Services, 2018).

Perceptions play a central role in shaping how ES are recognised, valued, and acted upon. Individuals and communities perceive ecosystem conditions and benefits through lived experience, cultural norms, and social contexts, which in turn influence behaviours, management preferences, and support for governance interventions. Empirical studies have shown that perception-based assessments can reveal dimensions of ES that are overlooked by biophysical indicators alone, particularly for regulating and cultural services (Bai et al., 2024; Thiemann et al., 2022).

In freshwater systems, perceptions of WQ, ecosystem health, and service provision are especially relevant, as they directly influence behaviours related to water use, protection, and collective action. Valenzuela & del Valle Barrera (2023) emphasise the importance of integrating social perceptions and relational values into ES assessments to enhance their relevance for local decision-making and governance. Such approaches support the recognition of non-material benefits, power relations, and context-specific meanings that are central to sustainability outcomes.

By incorporating perceptions, recognition, and relational values, ES valuation moves beyond extractive or purely technocratic models toward a more reflexive and participatory process. Perceptions act as key mediating factors between ecological conditions and human behaviour, shaping individual and collective responses such as resource use, stewardship, compliance with regulations, and support for management interventions. At the same time, the recognition of ES is not value-neutral: perceptions and values are unevenly represented across social groups and institutional settings, reflecting power asymmetries and differing capacities to influence decision-making processes. Acknowledging these dynamics is essential for understanding how ES are translated, or fail to be translated, into governance outcomes. Consequently, integrating perception-based and relational valuation into ES assessment provides a critical foundation for adaptive and inclusive water governance, and directly motivates the transdisciplinary and co-production approaches discussed in the following section.

2.2.3 Knowledge co-production and transdisciplinarity

The increasing complexity of social-ecological systems and sustainability challenges has exposed the limitations of disciplinary and expert-driven approaches to environmental assessment and decision-making. Within sustainability science, ES have been widely recognised as a boundary concept capable of linking ecological processes with human well-being; however, their effective application depends on how knowledge is produced, integrated, and legitimised across scientific, social, and institutional domains. In this context, knowledge co-production and transdisciplinarity have emerged as essential approaches for addressing the normative, epistemic, and governance dimensions of ES.

In this research, ES are understood as contributions from nature to human life and well-being. At the same time, it is acknowledged that ecosystems sustain not only human societies but also other life forms and ecological processes, a perspective that aligns more closely with the Nature's Contributions to People (NCP) framework. This conceptual distinction highlights a central tension in ES research: while ES often emphasise human benefits, NCP explicitly recognises plural worldviews, relational values, and non-anthropocentric perspectives (Intergovernmental Platform on Biodiversity and Ecosystem Services, 2018). Rather than treating these perspectives as mutually exclusive, this research adopts ES as an operational analytical framework, while drawing on NCP to broaden the recognition of values, meanings, and knowledge systems.

A key implication of this positioning is the rejection of reductionist valuation approaches that equate value with monetary price. Ecological economics has long emphasised that many ecosystem values are incommensurable and cannot be adequately expressed through a single metric (Martínez-Alier & Muradian, 2015). From this perspective, valuation is not a purely technical exercise, but a social and ethical process involving recognition, deliberation, and negotiation of values. In this

research, valuation is therefore intentionally non-market and perception-based, reflecting an epistemic commitment to plural valuation and strong sustainability principles. This approach is theoretically aligned with Max-Neef's framework of human needs, values and transdisciplinary perspectives to sustainability (Max-Neef, 2005; Valenzuela & del Valle Barrera, 2023).

2.2.3.1. Knowledge co-production

Knowledge co-production provides the methodological and epistemological foundation for operationalising this plural and non-reductionist understanding of ES. Co-production refers to processes through which knowledge is jointly produced by scientists, practitioners, decision-makers, and affected communities, integrating different forms of expertise, experience, and values (Norström et al., 2020). Within sustainability science, co-production is closely associated with post-normal science, where facts are uncertain, stakes are high, and values are contested (S. O. Funtowicz & Ravetz, 1993; S. Funtowicz & Ravetz, 2025). In such contexts, extending the peer community beyond academia is not only desirable but necessary for producing socially robust and actionable knowledge.

In freshwater social-ecological systems, local and experiential knowledge plays a particularly important role. Communities interact directly with water bodies through consumption, livelihoods, cultural practices, and daily observation, generating situated knowledge about WQ, ecosystem change, and service provision that cannot be fully captured through biophysical indicators alone (Bai et al., 2024; Thiemann et al., 2022). At the same time, technical-scientific knowledge derived from RS, modelling, and statistical analysis provides spatially explicit, temporally consistent, and scalable insights into WQ dynamics and ecosystem functioning. Knowledge co-production does not seek to replace one form of knowledge with another, but to integrate them through dialogue, mutual learning, and reflexive interpretation. Knowledge co-production requires reflexivity about power relations and representation because dominant knowledge systems often overshadow marginalised voices, limiting equitable participation and outcomes. Acknowledging these asymmetries prevents merely symbolic inclusion and supports more democratic, inclusive processes that integrate diverse perspectives and sustain adaptive environmental governance (Turnhout et al., 2020; Wyborn et al., 2019).

In this research framework, knowledge co-creation involves the interaction of multiple institutional levels and actors, including local communities, self-organised neighbourhoods, municipalities, universities, and other stakeholders. Universities and research institutions contribute technical-scientific expertise, methodological rigor, and access to global datasets and analytical tools. Municipalities and public agencies provide governance contexts, regulatory frameworks, and decision-making arenas. Communities and local stakeholders contribute contextual knowledge, perceptions, values, and lived experience. The integration of these actors reflects a polycentric governance perspective consistent with social-ecological systems

theory, where decision-making authority and knowledge are distributed across scales and institutions.

2.2.3.1. Transdisciplinarity, as a dialogue of knowledge

Transdisciplinarity extends beyond interdisciplinarity by explicitly engaging non-academic actors in the production of knowledge and by orienting research toward real-world problem-solving (Lang et al., 2012). In transdisciplinary research, problem framing, knowledge generation, and solution development are iterative and collaborative processes. This approach is particularly relevant for ES valuation, where the meaning, importance, and legitimacy of services depend on social recognition and institutional context. Valenzuela & del Valle Barrera (2023) emphasise that perception-based and participatory valuation approaches enhance the relevance of ES assessments by aligning them with local priorities, governance needs, and cultural values.

Within this thesis, transdisciplinarity is operationalised as a knowledge integration pathway that links EO and ML-based WQ indicators with social perceptions, human needs, and institutional decision-making. ES function as an intermediary language that facilitates communication between biophysical analysis and societal values, while co-production processes ensure that valuation outcomes are socially grounded and context-sensitive. This integration supports not only improved understanding of freshwater ES, but also their translation into governance-relevant knowledge.

In summary, knowledge co-production and transdisciplinarity provide the epistemological and methodological foundation for integrating ES modelling, non-market valuation, and human well-being within a social-ecological system's framework. By combining technical-scientific analysis with perception-based valuation and institutional engagement, this research advances a transdisciplinary knowledge integration framework for freshwater ES that is consistent with strong sustainability, plural valuation, and sustainability science.

2.3 Conceptual Integration: A Social Ecological Knowledge Pathway

Understanding and managing water systems in the context of accelerating environmental change requires conceptual frameworks capable of integrating biophysical processes, social dynamics, and normative sustainability goals across scales. Building on the theoretical foundations outlined in Sections 2.1 and 2.2, this research adopts a Social-Ecological Knowledge Pathway that explicitly links system ontology, modes of knowing, and governance-relevant action. Rather than

proposing a new unifying theory, the framework articulates a structured pathway through which diverse forms of knowledge are generated, integrated, and mobilised to support sustainable water governance under conditions of complexity and uncertainty. Figure 2 synthesises this pathway as a set of concentric domains, reflecting both the stratified nature of social-ecological reality and the iterative, co-evolutionary processes through which knowledge and action emerge.

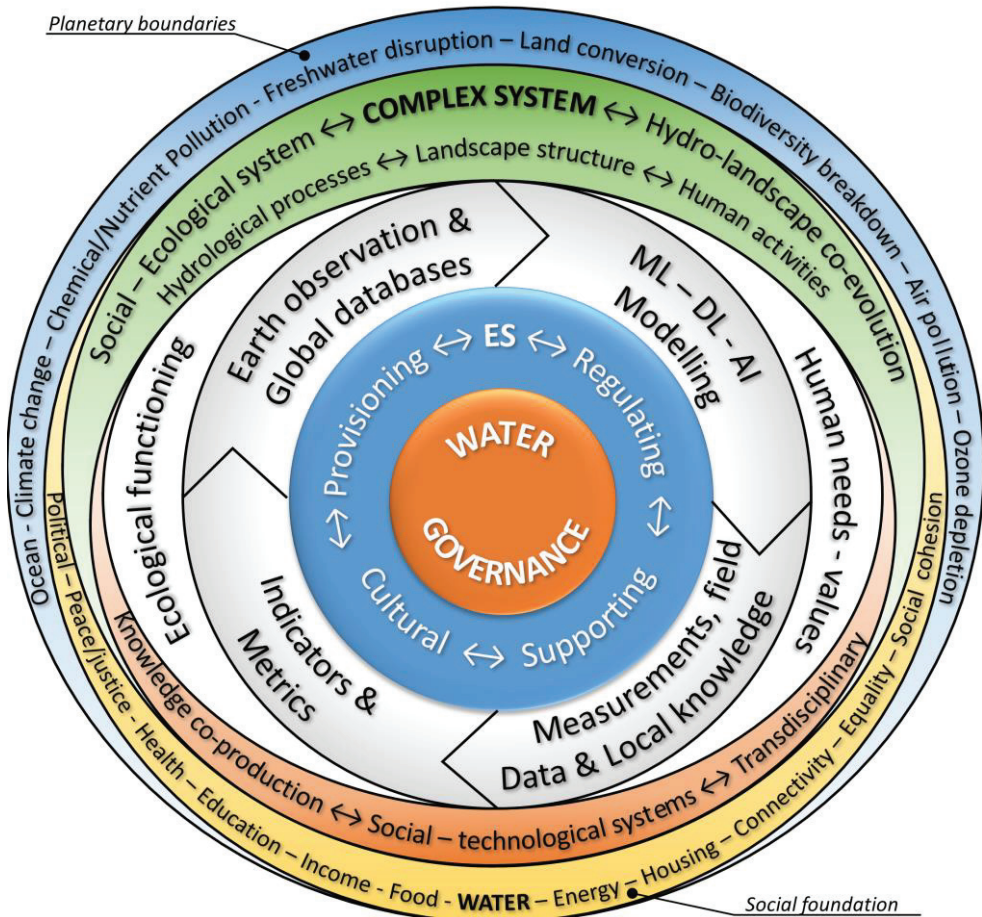


Figure 2. Conceptual integration of a social-ecological knowledge pathway for water governance. The framework situates hydro-landscape co-evolution within a broader social-ecological system, linking biophysical processes and landscape structure to ecosystem services and governance through Earth observation, machine learning, and socio-cultural valuation. Knowledge integration occurs through transdisciplinary co-production, enabling actionable insights under conditions of complexity and uncertainty.

2.3.1 Normative boundary conditions: sustainability constraints

The outermost domain of the framework situates water systems within a safe and just operating space, drawing from sustainability science concepts such as planetary boundaries and the social foundation. In this framing, water-related processes are simultaneously constrained by global biophysical limits (e.g., freshwater availability, biogeochemical flows, climate change) and by social imperatives related to equity, access to water, energy, food, and human dignity. Importantly, these constraints do not prescribe specific management actions but instead provide boundary conditions that shape the goals and evaluation criteria of water governance. By explicitly embedding these sustainability limits in the conceptual framework, the research acknowledges that water governance is inherently normative and cannot be reduced to technical optimisation alone.

Nested within these sustainability constraints is a domain representing the epistemic challenges inherent to hydrological and social-ecological research. This includes long-recognised unresolved problems in hydrology related to non-linearity, emergence, scaling, prediction under change, and the limits of observability. These challenges underscore that water systems cannot be fully known, controlled, or predicted, particularly in coupled human-natural contexts.

This recognition aligns with complex systems thinking and critical realism, acknowledging a stratified reality in which underlying processes (the real) generate observable system states (the actual), which are only partially accessible through empirical observation (the empirical). In this sense, uncertainty is not merely a data limitation but a fundamental property of the system. The framework therefore legitimises the use of probabilistic, data-driven, and exploratory approaches, such as ML, not as predictive panaceas, but as tools for inference, pattern detection, and hypothesis generation under deep uncertainty.

2.3.2 Social-ecological system ontology and hydro-landscape co-evolution

At the core ontological level, the framework conceptualises water systems as social-ecological systems (SES) characterised by dynamic interactions among hydrological processes, landscape structure, and social dynamics. Within this domain, the concept of hydro-landscape co-evolution is employed as a supporting spatial lens to emphasise the reciprocal shaping of water flows, landscape configuration, ecological processes, and human activities.

The hydro-landscape is not treated as an independent object of governance, but rather as the spatially explicit biophysical interface through which social-ecological interactions become manifest and observable. This perspective foregrounds connectivity, spatial heterogeneity, and scale dependencies, which are central to understanding WQ dynamics, ecosystem functioning, and the distribution of ES. By embedding the hydro-landscape within the broader SES ontology, the framework

avoids representing it as a standalone concept while retaining its analytical value for spatially explicit analysis.

2.3.3 Knowledge generation, ecosystem services to governance

This section conceptualises knowledge generation as a critical epistemic layer linking complex social-ecological dynamics to governance. Within the framework, this domain integrates EO, global databases, *in situ* monitoring, and modelling approaches to produce spatially explicit and actionable representations of system states and trajectories. EO offers synoptic and repeatable observations of key biophysical variables, while *in situ* data ground these observations in local hydrological and ecological processes. ML and statistical modelling are used to explore non-linear relationships, identify cross-scale patterns, and assess sensitivities to natural and anthropogenic drivers.

The outputs of this knowledge generation layer are expressed as indicators and proxies, such as WQ metrics, landscape configuration indices, and ecosystem condition indicators, that function as boundary objects between scientific analysis and governance processes. Consistent with a critical realist perspective, these representations are treated as partial and provisional models of reality, subject to revision as data availability, methods, and conceptual framing evolve.

Building on this epistemic foundation, the framework positions ES as a mediating interface between biophysical system states and human well-being. ES are understood as relational outcomes emerging from interactions among ecological condition, spatial configuration, hydrological connectivity, and social context, rather than as static or purely economic outputs. This perspective enables the explicit consideration of trade-offs and synergies among services and supports plural valuation approaches.

To capture the social relevance of ES, the framework incorporates a domain of human needs, values, and well-being, informed by human-scale development perspectives such as Max-Neef's fundamental needs. This layer emphasises that water-related benefits are perceived and prioritised differently across social groups and governance contexts, enabling the integration of socio-cultural valuation and behavioural dimensions.

At the core of the framework lies knowledge co-produced for ultimate water governance aim, understood as a cross-cutting, iterative process involving scientists, stakeholders, and decision-makers. This central integration supports reflexive learning, clarifies system relationships, and makes uncertainties explicit, thereby enabling context-sensitive and adaptive water governance rather than prescriptive solutions.

2.3.4 Implications for this research

This conceptual framework provides the integrative foundation for the empirical analyses presented in subsequent chapters. It justifies the combined use of EO, ML, landscape analysis, and socio-cultural valuation within a coherent epistemological structure, while situating empirical findings within broader sustainability and governance contexts. By explicitly linking system dynamics, knowledge generation, and human values, the framework enables this research to contribute not only to scientific understanding, but also to the co-production of knowledge relevant for sustainable water governance in complex social-ecological systems.

3 Study Area

Despite the global relevance of Andean freshwater systems, integrated studies spanning lakes and streams across strong altitudinal, climatic, and human-impact gradients remain scarce. This thesis addresses this geographical gap by focusing on small high Andean lakes and headwater streams in the Central Andes, linking regional-scale Andean processes with detailed analyses of three contiguous, socio-ecologically contrasted watersheds.

3.1 Andean lakes - [Papers I-II]

The Andes constitute the longest continental mountain range on Earth, extending over more than 8,000 km along western South America and spanning tropical to temperate latitudes (Figure 3a). This vast latitudinal and altitudinal extent generates extraordinary environmental heterogeneity, making Andean freshwater systems among the most diverse and complex globally (Prado et al., 2024). Lakes and streams in the Andes play a critical role in regional water security, biodiversity conservation, and ES provision, despite representing a relatively small fraction of continental surface waters.

Andean lakes are heterogeneous, ranging from large tectonic lakes to numerous small, shallow, and often endorheic water bodies located at high elevations. Recent syntheses developed in Paper I (Prado et al., 2024) highlight that many Andean lakes, especially small systems, remain underrepresented in limnological research, despite their importance as biodiversity refuge and natural regulators of hydrological and biogeochemical cycles. These lakes are typically subject to extreme environmental conditions, including high solar radiation, large diurnal temperature ranges, low atmospheric pressure, and strong seasonality in water balance.

Across the Andes, both lakes and streams are increasingly exposed to multiple stressors. This is particularly examined for lakes in Paper II (Campero et al., 2024). Climate change is altering precipitation regimes, increasing temperature, and modifying evapotranspiration rates, with cascading effects on water availability, thermal structure, and biogeochemical functioning. Concurrently, human pressures such as agriculture, mining, hydropower development, urban expansion, and water abstraction are intensifying, particularly in inter-Andean valleys and foothill

regions. Recent studies emphasise that these drivers do not act in isolation; rather, they interact with natural gradients, producing nonlinear and spatially heterogeneous responses in WQ and ecosystem functioning.

A growing body of literature underscores the need for integrated approaches that jointly consider lakes and streams within a catchment framework (Jiménez-Navarro et al., 2023; Kaval, 2019). Such perspectives are particularly relevant in the Andes, where strong topographic connectivity links upland headwaters, high-elevation lakes, and downstream rivers. Recent regional assessments highlight critical knowledge gaps in the Central Andes, especially regarding small high-elevation systems and their role in regulating carbon dynamics, nutrient cycling, and water-related ES under changing environmental conditions (Campero et al., 2024; Prado et al., 2024; Quenta-Herrera et al., 2022). Addressing these gaps is essential for improving predictive understanding and informing sustainable water management in Andean regions.

3.1.1 Small high Andean lakes (SHAL) and streams in Central Andes

Small high Andean lakes (SHAL) of the Glacial lakes in the Eastern Range District (Figure 3b; Prado et al., 2024) are defining features of this region, typically occurring above 4,000 m a.s.l. These systems are embedded within variable and extreme climatic conditions dominated by low temperatures, high solar irradiance, strong winds, and pronounced hydrological seasonality. Most SHAL are shallow, exhibit a cold polymictic thermal regime, and present short water residence times, moderate to high nutrient concentrations, making them highly responsive to atmospheric forcing and catchment-scale processes. Optical properties of water, including Chl-*a* and CDOM, are closely linked to both in-lake processes and terrestrial inputs, which are in turn modulated by elevation, soil development, and vegetation cover. Recent studies suggest that high-altitude lakes can play a significant role in regional carbon cycling, acting alternately as sinks or sources of carbon depending on hydrological conditions and human influence (Alcocer et al., 2020; Y. Li et al., 2025; Sánchez Valdivia et al., 2024).

Central Andean streams are predominantly headwater systems, characterised by steep gradients, short flow paths, and strong coupling between terrestrial and aquatic environments. Headwater streams generally have narrow channels, shallow depths, and high edge-area ratios, which enhance exchange of water, nutrients, and organic material with adjacent soils and riparian zones, making them highly responsive to local hydrological changes and terrestrial inputs (Battin et al., 2008; Gordon et al., 2004; Richardson & Danehy, 2007). These physical and hydrological traits strongly influence ecosystem processes and connectivity within mountain catchments. These streams often exhibit flashy hydrological responses, high sediment transport, and pronounced physicochemical variability, particularly in semi-arid and arid regions of the Central Andes. Such characteristics make them highly sensitive to climatic

variability and land-use change (Fustos-Toribio et al., 2025; Vagheei & Boano, 2025)

SHAL and streams hydrology is tightly controlled by precipitation seasonality, cryospheric processes, and groundwater contributions, with marked contrasts between wet and dry seasons driven largely by the South American summer monsoon (Espinoza et al., 2020) and modulated by the El Niño Southern Oscillations (ENSO; Garreaud et al., 2019). The sharp contrast between wet and dry seasons governs water levels, connectivity among aquatic systems, and solute concentrations. During the dry season, reduced inflows and enhanced evaporation often lead to increased concentrations of dissolved constituents, whereas the wet season promotes dilution and enhanced lateral connectivity. As runoff is a primary control of NPS pollution from catchments to aquatic systems, these seasonal dynamics strongly influence the transport of nutrients and organic matter (Krishnaraj & Honnasiddaiah, 2023; Xue et al., 2025).

Ecologically, SHAL and headwater streams support specialised and often endemic biota adapted to extreme environmental conditions. Puna grasslands and *bofedales* (high-Andean wetlands) surrounding these water bodies are integral components of the aquatic-terrestrial continuum, regulating hydrological fluxes, trapping sediments, and mediating nutrient and carbon exchanges (Navarro & Ferreira, 2007; Sánchez Valdivia et al., 2024). The integrity of these ecosystems is therefore crucial for maintaining downstream WQ and ES.

Despite their importance, SHAL and headwater streams in the Central Andes remain poorly studied compared to lowland and large-lake systems. Existing research has often focused on isolated lakes or single variables, thereby limiting the ability to generalise across gradients of climate, topography, and human influence (Batina & Krtalić, 2024; Xia et al., 2024). Moreover, increasing pressures from water abstraction, reservoir construction, hydropower development, and urban expansion are rapidly transforming these systems. This highlights the need for integrated, multi-scale studies that capture both natural variability and anthropogenic influences across connected aquatic ecosystem networks.

3.2 Study sites - [Papers III-V]

The study area is located in the Central Andes of Bolivia (approximately 17° S, 66° W), within the upper Amazon River basin, and encompasses three contiguous mountain watersheds situated along the southern flank of the Cordillera Oriental (GADC, 2019; GAMQ, 2021). These watersheds are part of the Cochabamba Valley region and fall mainly within the administrative boundaries of the Quillacollo Municipality, with partial inclusion of the Colcapirhua and Tiquipaya municipalities. A substantial portion of the area lies within Tunari National Park, a

protected area of high ecological and hydrological significance (Figure 3c; SERNAP, 2016).

Together, the watersheds cover an altitudinal range from approximately 2,531 m a.s.l. in the lower valleys to over 5,000 m a.s.l. at the highest peaks, including Tunari Peak. This elevation gradient generates pronounced climatic contrasts, ranging from cold semi-arid (BSk) conditions in the lower catchments, to temperate highlands climates (Cwb) with dry winters and warm summers at mid-elevations, and polar tundra (ET) conditions in the highest zones, following the Köppen & Geiger (1936) classification (Cui et al., 2021). Mean annual air temperatures decrease from about 17 °C in the lower areas to approximately 11 °C in the headwaters, while precipitation generally increases with elevation and is strongly seasonal (MMAyA, 2023; SENAMHI, 2025).

The landscape is characterised by a mosaic of mountains, foothills, and inter-Andean plains formed within an intramontane tectonic basin. The geological framework comprises Paleozoic and Mesozoic formations overlain by Cenozoic sediments (Renner & Velasco, 2000), giving rise to diverse soil types and geomorphological units (Beek & Wright, 1971; Gouzes & Depont, 1990; Neumann-Redlin et al., 2000). Vegetation follows clear altitudinal patterns, transitioning from agricultural and urban landscapes in the lower valleys to puna grasslands, *bofedales*, and sparsely vegetated high-mountain environments at higher elevations (Navarro & Ferreira, 2007; Navarro & Maldonado, 2002).

Human influence varies markedly across the study area, creating a gradient from relatively pristine headwaters within protected zones to intensively managed and urbanised lower catchments. Anthropogenic modification dates back to pre-Columbian agricultural practices but intensified substantially during the twentieth century with the construction of irrigation infrastructure and, more recently, large-scale hydropower and water-transfer projects. Irrigation System No (GAMQ, 2021). 1, established in 1945, and the Masicuni multipurpose project, operational since 2018, have reconfigured natural flow paths through inter-basin transfers and regulated discharges of approximately $1 \text{ m}^3 \text{ s}^{-1}$ (Contraloría General del Estado Plurinacional de Bolivia (CGE), 2020; Empresa Nacional de Electricidad CORANI (ENDE), 2023).

As of 2024, the population within the study area exceeds 165,000 inhabitants, with the vast majority residing in urban zones (Instituto Nacional de Estadística, 2025). While access to electricity is nearly universal, coverage of freshwater distribution and sewage systems remains incomplete, resulting in widespread discharge of untreated wastewater into local streams (Instituto Nacional de Estadística, 2025). Economic activities are dominated by agriculture and industry, with cropping patterns strongly conditioned by elevation, water availability, and infrastructure connectivity (GAMQ, 2021; Prado et al., 2025).

The combination of strong topographic and climatic gradients, diverse aquatic systems, and contrasting levels of human impact makes these three contiguous watersheds an ideal natural laboratory. They integrate natural and anthropogenic

drivers typical of the Central Andes and provide a unique setting to assess, WQ dynamics, and biogeochemical processes across coupled high-elevation freshwater systems, while explicitly accounting for gradients of protection status, LULC, and water infrastructure development. This integrated context is particularly suitable for evaluating how climatic variability and human interventions jointly shape water-related ES in Andean headwaters.

Paper III focused on stream ecosystems across the Chocaya (CHO) and Chijllawiri (CHI) watersheds, capturing the influence of LULC and precipitation on WQ variability along several spatial scales ranging catchment, riparian zones, reach and accumulating effects from upstream. Paper IV examined seven SHAL and the Misicuni reservoir located within the Misicuni and CHO watersheds, spanning elevations from approximately 3,774 to 4,608 m a.s.l. These lakes are mostly regulated systems that provide freshwater for local communities, irrigation, and urban supply, while the Misicuni reservoir forms part of a multipurpose infrastructure supplying drinking water, irrigation, and hydropower to the Cochabamba metropolitan region (GADC, 2019). Paper V integrated these lake and stream systems to assess freshwater ES across the three contiguous watersheds under contrasting levels of human influence.

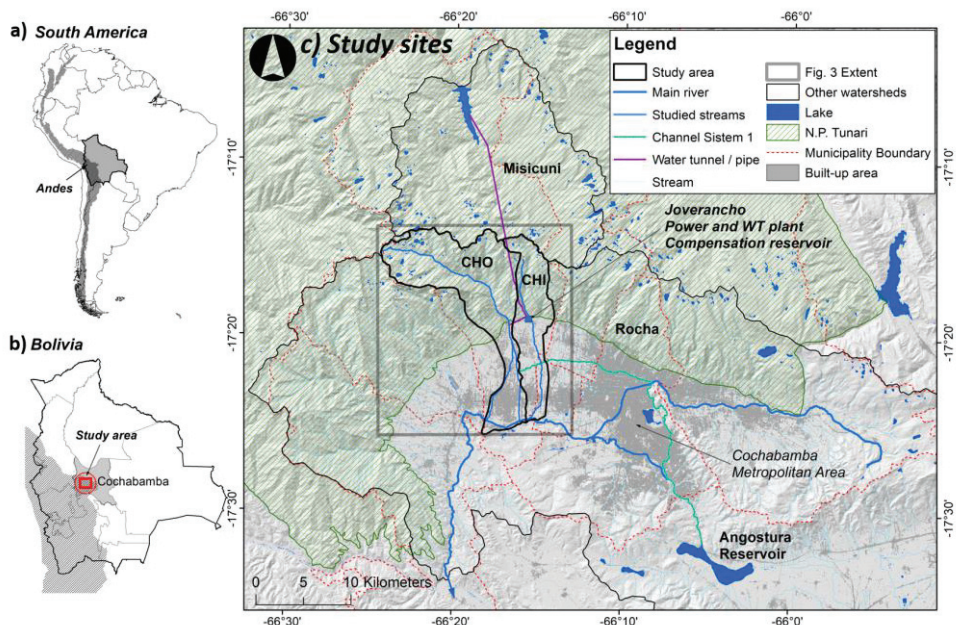


Figure 3. Study area overview. (a) Location of the Andean Cordillera within South America; (b) Glacial lakes in the Eastern Range District of the Central Andes, Bolivia; and (c) study sites located in three adjacent watersheds: Chocaya (CHO), Chijllawiri (CHI), and Misicuni. Figure from Paper III: Prado et al. (2025)

4 Materials and Methods

This thesis contributes to knowledge through methodological innovations developed in the appended papers and through their integration within an analytical, cost-effective, and scalable framework. The novelty lies in combining global datasets, RS-derived WQ indicators, ML modelling, field data, and socio-economic perceptions to support freshwater ES valuation and evidence-based integrated sustainable water management. This section provides a commented summary of field data collection, global data sources, ML approaches, key indicators of WQ, ES assessment and valuation, and concludes with a subsection on framework integration and analytical workflow (Figure 4).

4.1 Field data collection and laboratory analysis

Field data collection was designed to address the limited availability of *in situ* observations in remote and data-scarce regional freshwater systems. Targeted sampling campaigns were therefore essential to support the integration of global databases, satellite-derived indicators, and modelling outputs. This subsection summarises field data acquisition across three complementary components: (i) physicochemical and nutrient monitoring in streams and irrigation channels, (ii) lake and reservoir surface water measurements and sampling for optical and biogeochemical characterisation, and (iii) a watershed-scale survey capturing socio-economic perceptions of freshwater ES.

4.1.1 Stream and irrigation channels sampling [Paper III]

Stream and irrigation channel monitoring was conducted using a spatially distributed network of 17 sampling locations positioned along second-order tributaries within the CHO and CHI catchments. Seasonal campaigns carried out between 2022 and 2024 yielded 81 discrete samples representing contrasting hydrological conditions. Sub-surface water (~10 cm) was collected following contamination-minimisation procedures and preserved under cold-chain conditions during transport.

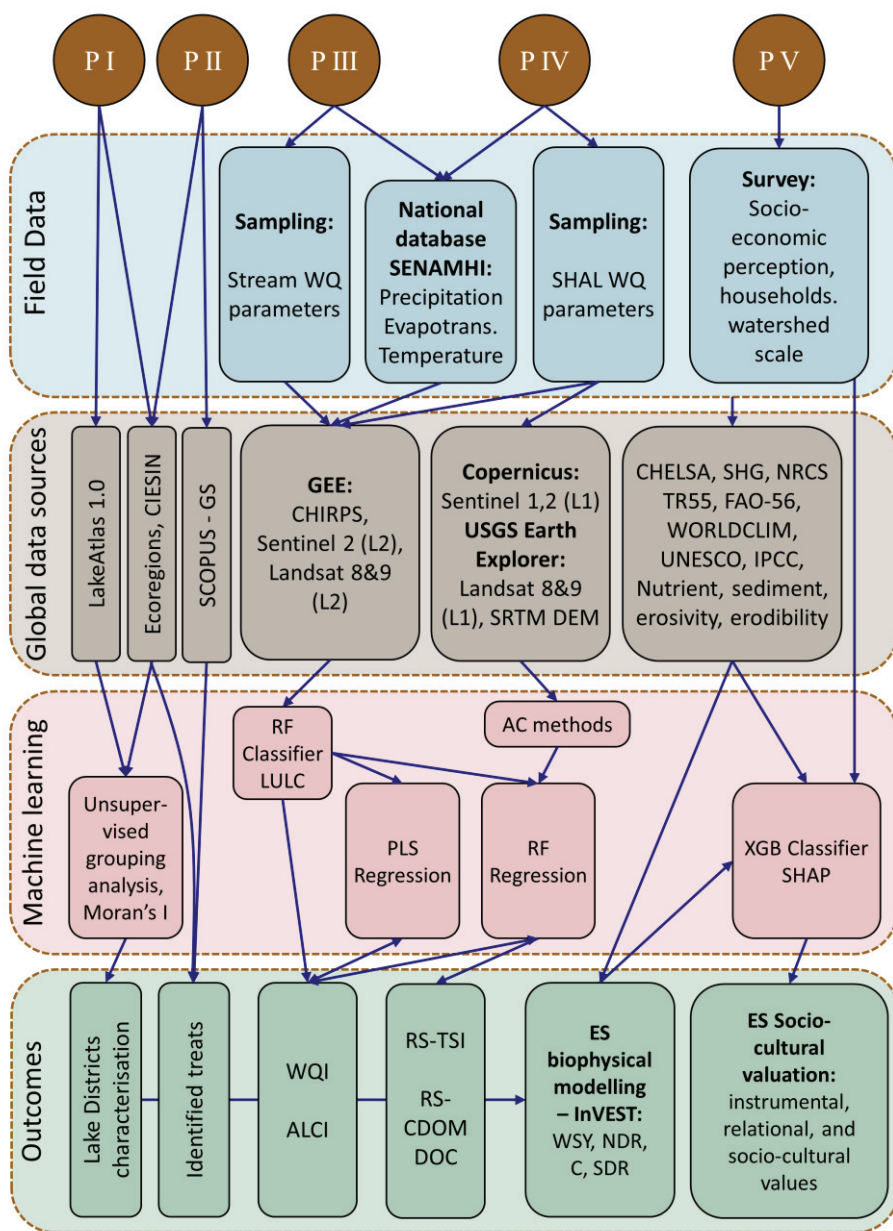


Figure 4. Overview of the analytical workflow used in this research, showing the integration of field data and global data sources, subsequent ML analyses, and key outcomes. Arrows indicate data flows and methodological linkages across Papers I–V. WQ: water quality; SHAL: small high-Andean lakes; GEE: Google Earth engine; AC: atmospheric correction. Additional acronyms are provided in the Abbreviations section.

Laboratory analyses covered a broad suite of physicochemical and nutrient variables using internationally standardised protocols (APHA, 2023; ISO 8467:1993), from which a reduced set of key indicators was retained for subsequent analyses (Total Phosphorus, Chemical oxygen demand, Nitrate, Permanganate index, Total iron, Manganese, Total coliforms, Thermotolerant coliforms, Total solids, Total dissolved solids, Suspended solids, Dissolved oxygen, Turbidity, Electrical conductivity, Hydrogen potential).

4.1.2 SHAL and reservoir sampling [Paper IV]

Surface-water sampling in lakes and a reservoir was performed during pre-rainy, rainy, and post-rainy periods (2023-2024) to characterise seasonal variability. Sampling points were georeferenced and distributed to represent within-waterbody heterogeneity, with an emphasis on sub-surface (10-50 cm) layers observable by satellite sensors. Core limnological variables were measured *in situ* using calibrated multiparameter instrumentation and a Secchi disk for water transparency. While laboratory analyses focused on Chl-*a*, CDOM, and DOC. Samples were filtered, preserved, and transported under light- and temperature-controlled conditions to ensure analytical integrity.

Chl-*a* concentrations were quantified fluorometrically following ethanol extraction (95%) and calibration against certified standards (Modenutti et al., 2013; Sigma-Aldrich). CDOM optical properties were characterised from UV-Vis absorbance spectra (190-1100 nm) of 0.22 µm-filtered samples measured in quartz cuvettes, with absorption coefficients computed using the Lambert-Beer formulation (Twardowski et al., 2004). DOC was analysed via high-temperature catalytic oxidation after filtration and acidification.

4.1.3 Socio-economic perception survey [Paper V]

Socio-economic data were collected through a stratified household survey designed to capture spatial, climatic, and LULC gradients across the watershed, during September-October 2024. The questionnaire, developed in collaboration with municipal authorities and domain experts, addressed socio-demographic characteristics and perceptions of freshwater ES. Data collection combined digital and paper-based formats to ensure inclusivity in remote areas with limited connectivity (Almeida et al., 2018). Trained survey teams followed ethical guidelines, multilingual protocols, and systematic quality-control procedures, supported by pilot testing, stakeholder coordination, and ongoing validation during implementation.

Data preparation began with rigorous quality control to ensure database consistency. Invalid or contradictory entries were removed, and incomplete responses (e.g., missing values, “don’t know,” or no answer) were systematically

recoded using dedicated numeric flags (98 and 99). Categorical inconsistencies were harmonised through standardised labelling. Ordinal variables obtained from five-point Likert-scale questions were converted into numerical values to facilitate quantitative analysis. The Likert scale is a widely used approach for assessing attitudes and preferences in social research (Likert, 1932; Schmidt et al., 2017), allowing respondents to express the perceived importance of each service and thereby translating subjective evaluations into ordinal data. Composite perception indices were generated, and a documented codebook was produced.

4.2 Global data sources

Global databases and EO products were fundamental for extending locally collected data across spatial and temporal scales, particularly in this study region where long-term monitoring is absent. Freely accessible global datasets enabled the systematic integration of hydrological, climatic, geomorphological, LULC, and WQ proxies with field observations. This subsection summarises the use of open-access lake and watershed inventories, satellite imagery, climate and hydrological datasets, and cloud-based processing platforms, particularly GEE, that supported spatial analyses, model inputs, and cross-scale comparisons throughout core components of this thesis.

4.2.1 Andean lakes characterisation [Papers I & II]

Large-scale lake analyses were based on LakeAtlas 1.0 (Lehner et al., 2022), from which a subset of lakes was extracted by spatially intersecting the study region and excluding artificial reservoirs, dams, and boundary lakes. The final dataset comprised 5,071 natural lakes larger than 0.1 km², enabling consistent regional mapping and comparative analyses. Variables such as elevation, residence time, air temperature, precipitation, potential evapotranspiration were obtained directly from LakeAtlas, while ecoregions from Griffith et al. (1998), and population density data were sourced from (CIESIN, 2018) and (SEDAC, 2023). This harmonised dataset supported spatial assessments of lake distribution and human-lake interactions at regional scales.

4.2.2 LULC and precipitation influence on WQ [Paper III]

Hydroclimatic drivers were characterised using global precipitation and satellite datasets to complement sparse gauged observations from the national hydrology and meteorology service (SENAMHI). Daily precipitation from CHIRPS (Funk et al., 2015) was bias-adjusted using nearby station records and applied to estimate

catchment-scale runoff through a rational-method framework (Brutsaert, 2023). LULC conditions corresponding to sampling periods were derived from Sentinel-2 and Landsat 8&9 imagery processed within GEE. Ancillary topographic variables, including slope and TWI, were extracted from a hydrologically corrected DEM processed in SNAP from Sentinel-1. Supervised LULC classifications were generated using RF algorithms on the inputs, producing seasonally consistent LULC maps suitable for watershed-scale analysis.

4.2.3 Remote-sensed WQ indicators of SHAL [Paper IV]

Catchment delineation and hydroclimatic characterisation relied on globally available elevation, precipitation, and satellite datasets. A void-filled SRTM DEM (30 m) was processed to derive flow direction, accumulation, and lake-specific catchment boundaries using GRASS GIS tools. Daily CHIRPS precipitation data were retrieved via GEE and validated against records from SENAMHI meteorological stations. ML-based (RF) bias correction was applied to improve precipitation estimates, generating spatially continuous, station-adjusted rainfall time series. These data were used to compute antecedent precipitation metrics aligned with field sampling dates. LULC classifications were produced using a transferable RF workflow developed in Paper III, and aggregated indicators such as the Anthropogenic Land Cover Index (ALCI) were derived to quantify human pressure within lake catchments.

In parallel, Sentinel-2 MSI and Landsat 8&9 OLI/TIRS imagery closest to each sampling date were acquired to minimise temporal mismatch with field observations. Multiple AC processors (C2RCC, iCOR, ACOLITE) were applied alongside standard Level-2 products available in GEE (Gorelick et al., 2017), enabling cross-processor evaluation of surface reflectance retrievals over optically complex high-altitude lakes. Corrected imagery was harmonised within a Python-based workflow to extract reflectance values and compute spectral indices and band ratios relevant to WQ assessment.

4.2.4 Ecosystem services modelling [Paper V]

ES modelling integrated a suite of global spatial datasets as inputs to the InVEST framework. These included LULC maps (developed in Paper III and IV), climate variables (precipitation and evapotranspiration), soil hydrological properties, digital elevation data, and standardised parameters for carbon pools, runoff generation, erosion, and nutrient transport derived from global and regional sources (Fick & Hijmans, 2017; Intergovernmental Panel on Climate Change, 2006; Karger et al., 2021; Panagos et al., 2023). Climate classifications and rainfall-event definitions were incorporated to contextualise hydrological processes. Together, these datasets

enabled spatially explicit assessment of ES, while ensuring methodological consistency and comparability across scales.

4.3 Machine learning modelling

Multiple ML approaches were required to address the diversity of research objectives, data structures, and spatial scales explored in this thesis. Unsupervised methods were used to identify emergent spatial-environmental patterns without prior assumptions, while supervised classification and regression models enabled the prediction and quantification of categorical and continuous variables derived from RS, global datasets, and field observations. These complementary approaches allowed landscape characteristics, hydroclimatic drivers, and socio-economic variables to be integrated within the analytical framework. ML models were applied to support regional lake typologies, LULC mapping and its influence on WQ, lakes WQ prediction, and ES valuation. The following subsections describe the operational implementation of grouping analysis, tree-based classification and regression models, multivariate regression, and gradient-boosted classifiers as applied across the appended papers.

4.3.1 Unsupervised grouping analysis [Papers I & II]

Unsupervised grouping analysis is designed to delineate internally homogeneous and externally distinct spatial units based on multivariate similarity, without relying on predefined class labels (Chaudhry et al., 2023). In its foundational form, this approach follows a variance-minimisation principle consistent with k-means clustering, whereby observations are iteratively assigned to a fixed number of groups to minimise within-group dispersion in feature space (Jain, 2010; MacQueen, 1967). When implemented for spatial data, grouping can be extended through neighbourhood constraints to preserve geographic coherence and limit artefacts arising from purely statistical partitioning. In this context, spatial connectivity graphs such as Delaunay triangulation are used to restrict allowable group memberships, resulting in a spatially constrained k-means type algorithm that accounts for adjacency while maintaining multivariate similarity (Duque et al., 2012; Esri, 2023). The spatial structure of the resulting groups is commonly evaluated using global spatial autocorrelation metrics, such as Global Moran's I, to assess whether identified patterns reflect meaningful spatial organisation rather than random aggregation (Anselin, 1995; Moran, 1950).

An exploratory grouping analysis was applied to identify spatially coherent lake assemblages based on shared environmental and climatic characteristics, without imposing predefined class boundaries. This unsupervised approach was implemented using a group-wise and variable-wise clustering algorithm available

in the ArcGIS 10.8 spatial statistics toolbox, incorporating Delaunay triangulation to account for spatial proximity among observations. Multiple grouping configurations were initially explored by varying both the number of groups and the combinations of explanatory variables, allowing sensitivity to different environmental gradients to be assessed.

To ensure ecological relevance and regional consistency, the final analyses were stratified by the three main Andean zones (Northern, Central, and Southern Andes), corresponding to first-level ecoregions defined by Griffith et al. (1998). Separate grouping analyses were conducted within each zone to reduce large-scale biogeographic dominance and enhance within-region comparability. Input variables were selected based on their limnological significance and capacity to capture altitudinal, climatic, and hydrological gradients, and included elevation, lake residence time, mean air temperature, precipitation, potential evapotranspiration, and third-level ecoregion classifications.

Prior to grouping, variables were standardised to comparable scales to prevent dominance by high-magnitude predictors. The algorithm iteratively assigned lakes to groups by minimising within-group variance while maximising between-group dissimilarity across the selected variables, under spatial constraints imposed by the triangulation network.

To evaluate the spatial robustness of the resulting groupings, global spatial autocorrelation was assessed using Moran's I (Moran, 1950). This analysis tested whether grouped lakes exhibited significant spatial clustering beyond random expectation, thereby providing a quantitative measure of confidence in the spatial structure of the classification. The grouping outputs formed the basis for subsequent regional comparisons and supported the interpretation of large-scale lake patterns in relation to climate and landscape gradients.

4.3.2 Random forest classification [Papers III & IV]

RF classification is an ensemble learning technique that constructs multiple decision trees using bootstrapped subsets of the training data and randomly selected predictor variables at each split. Final class assignment is obtained through majority voting across the ensemble, which reduces variance and improves generalisation compared to single-tree classifiers. This stochastic structure makes RF particularly robust to noisy inputs, correlated predictors, and high-dimensional feature spaces, which are common in multi-sensor RS applications. RF classifiers are non-parametric and do not require assumptions about data distributions, allowing them to model complex, nonlinear class boundaries and interactions among spectral, textural, topographic, and climatic variables. Additionally, RF provides internal estimates of classification error and variable importance, facilitating model evaluation and interpretability. These characteristics have made RF one of the most widely adopted classifiers for LULC mapping across heterogeneous landscapes (Belgiu & Drăgu, 2016; Breiman, 2001; Pal, 2005).

RF classification was employed to map LULC conditions corresponding to field sampling periods, integrating multisensor RS data and ancillary environmental variables. Satellite imagery (Level-2 collection) from Sentinel-2 and Landsat-8&9 was processed within the GEE platform to derive surface reflectance and spectral indices, while Sentinel-1 (SNAP processed) synthetic aperture radar data were incorporated to enhance discrimination of land-cover types under variable atmospheric and surface conditions. Additional predictors, including land surface temperature, slope, and TWI, were derived from satellite-based elevation products.

All predictor layers were temporally aligned with field campaigns and spatially harmonised prior to classification. Supervised RF models were trained using manually curated reference samples representing eleven LULC classes, spanning natural, agricultural, and urban surfaces. Training datasets were split into independent calibration and validation subsets using an 80-20 proportion. The RF classifier was configured with 100 decision trees, allowing ensemble learning to reduce variance and improve classification stability across heterogeneous landscapes.

Model performance was evaluated using standard accuracy metrics widely applied in RS, including overall accuracy, Cohen's kappa coefficient, producer accuracy, and consumer accuracy (Cohen, 1960; Congalton, 1988; Lillesand et al., 2015; Stehman, 1997). These metrics provided complementary perspectives on classification reliability, accounting for both overall agreement and class-specific omission and commission errors.

Multiple LULC classifications were generated to represent contrasting hydrological conditions across seasons during 2023-2024. Post-classification processing included spatial filtering using a majority 3x3 moving window to reduce isolated pixel noise and improve thematic coherence. Classified rasters were subsequently clipped to watershed and lake-catchment boundaries, enabling the calculation of proportional land-cover metrics. Aggregated indicators, such as the Anthropogenic Land Cover Index (ALCI), were derived to summarise human land use pressure and support subsequent analyses of land-WQ interactions.

4.3.3 Random forest regression [Papers III & IV]

RF regression extends the ensemble tree framework to continuous response variables by aggregating predictions across multiple regression trees, each trained on a bootstrapped sample of the data. Individual trees partition the predictor space to minimise within-node variance, and final predictions are obtained by averaging across all trees, resulting in stable and low-bias estimates. RF regression is particularly effective for modelling nonlinear relationships and higher-order interactions without requiring explicit functional forms, making it well suited for environmental systems where responses emerge from complex couplings among landscape, climatic, and biophysical drivers. The method is resilient to multicollinearity and can accommodate predictors operating at different spatial and

temporal scales. Model interpretability is enhanced through feature importance measures derived from impurity reduction or permutation-based approaches, which allow identification of dominant drivers while preserving predictive performance (Breiman, 2001; Cutler et al., 2007; Liaw & Wiener, 2002).

RF regression was applied to quantify nonlinear relationships between RS climatic, and catchment-derived predictors and multiple WQ variables. Separate regression models were constructed for each response variable, allowing predictor-response relationships to be tailored to specific WQ indicators. Predictor datasets included land-cover proportions, precipitation metrics, elevation, and spectral variables, which were normalised prior to model fitting to ensure numerical stability.

Model development followed a structured workflow implemented in Python (Python Software Foundation, 2023). Hyperparameters controlling tree complexity and ensemble size (estimators number, max depth, min samples split, min samples leaf) were optimised using grid-search procedures combined with k-fold cross-validation and repeated random shuffling to enhance robustness. Model performance was evaluated using complementary metrics, including the coefficient of determination (R^2), root mean square error (RMSE), and cross-validation correlation coefficients, enabling assessment of both explanatory power and generalisation capacity.

Feature importance was examined using two complementary approaches: impurity-based importance derived from node splitting frequency and permutation-based importance assessing predictive degradation when individual predictors were randomly shuffled. These diagnostics supported the identification of dominant drivers and informed the development of reduced models using the most influential predictors.

The best-performing models for each response variable were retained for spatial prediction. Predictor layers were assembled into multiband raster stacks aligned with sampling dates, and predictions were generated at the pixel level across lake surfaces. Model uncertainty was quantified as the standard deviation of predictions across ensemble trees, producing spatially explicit confidence layers.

4.3.4 Partial least squares regression [Paper III]

Partial Least Squares Regression (PLSR) is a multivariate statistical technique designed to model relationships between a set of correlated predictors and one or multiple response variables by projecting both into a reduced latent space. Unlike ordinary least squares regression, PLSR maximises the covariance between predictors and responses, making it particularly effective in situations characterised by multicollinearity, limited sample sizes, and high predictor dimensionality. Each latent component represents a weighted combination of original variables, allowing simultaneous dimensionality reduction and regression. PLSR provides interpretable diagnostics, such as component loadings, regression coefficients, and Variable

Importance in Projection (VIP) scores, which quantify the relative contribution of predictors to model performance. These properties make PLSR a complementary approach to RF regression model, particularly for disentangling dominant linear structures and identifying consistent predictor–response relationships in environmental datasets (Abdi, 2010; Mehmood et al., 2012; Wold et al., 2001).

PLSR was implemented as a complementary multivariate approach to examine relationships between LULC composition and multiple stream WQ responses simultaneously. This method is well suited for datasets characterised by collinearity among predictors and limited sample sizes. PLSR models were developed using the same predictor sets as the RFR approach, with predictors normalised to ensure comparability across scenarios.

The optimal number of latent components was determined through k-fold cross-validation, balancing explained variance and model parsimony. Model outputs included regression coefficients, component loadings, and the proportion of variance explained in both predictor and response spaces. VIP scores were calculated to quantify the relative contribution of each predictor across components.

Model performance was assessed using standard goodness-of-fit and cross-validation metrics, including R^2 and RMSE. To synthesise insights across modelling approaches, PLSR-derived importance metrics were compared with RF feature importance rankings. The consistency between methods was evaluated using rank-based Spearman’s correlation, providing an integrated assessment of LULC influence on WQ across spatial scales.

4.3.5 Extreme gradient boost regression [Paper V]

Extreme Gradient Boosting (XGBoost) is a boosting-based ensemble learning algorithm that builds decision trees sequentially, with each new tree optimised to correct the residual errors of previous ones. Unlike bagging approaches, boosting focuses learning on difficult-to-classify observations, enabling improved performance on complex and imbalanced datasets. XGBoost incorporates regularisation, shrinkage, and subsampling strategies to control overfitting and enhance generalisation, while maintaining high computational efficiency. Its ability to model nonlinear relationships, variable interactions, and threshold effects makes it particularly suitable for socio-economic and perception-based data, including ordinal responses such as Likert-scale variables. Model interpretability can be enhanced using *post hoc* explanation tools such as Shapley Additive exPlanations (SHAP), which quantify the marginal contribution of each predictor to model outputs, thereby linking predictive performance with transparent inference (T. Chen & Guestrin, 2016; Lundberg & Lee, 2017).

XGBoost classifiers were applied to model categorical ES valuation outcomes derived from socio-economic survey data. This algorithm was selected for its ability to capture nonlinear relationships, handle mixed data types, and manage class

imbalance through regularisation and weighted learning. RF classifiers were implemented in parallel to provide methodological comparison.

Datasets were partitioned into training and validation subsets using stratified sampling to preserve class distributions. Hyperparameters governing tree depth, learning rate, ensemble size, and subsampling were optimised using grid-based cross-validation to minimise overfitting. Model performance was evaluated using multiple metrics, including overall accuracy, F1-score, and the area under the receiver operating characteristic curve (ROC-AUC), ensuring robust assessment under imbalanced class conditions.

To enhance interpretability, model-based importance scores were complemented with Shapley Additive exPlanations (SHAP; Lundberg & Lee, 2017). SHAP values enabled both global and local interpretation of model predictions, quantifying the direction and magnitude of each predictor's contribution. This approach facilitated integrated interpretation of how biophysical conditions, ES supply, accessibility, and socio-economic factors jointly influenced valuation outcomes.

4.4 Water quality key indicators

Integrative indicators are widely used to synthesise complex WQ information into interpretable metrics that support comparison across sites, seasons, and scales. Classical indices such as the Water Quality Index (WQI; R. M. Brown et al., 1970) remain valuable due to their conceptual simplicity, flexibility in parameter selection, and robustness when applied to heterogeneous datasets. In this thesis, WQI is complemented by the Anthropogenic Land Cover Index (ALCI), a novel indicator introduced in Paper III to quantify catchment-scale human pressure using LULC information. In parallel, trophic state is assessed through the Carlson Trophic State Index (TSI; Carlson, 1977), extended here by integrating RS-derived Chl-*a* predictions with hydroclimatic and landscape variables. DOC is additionally estimated using optically derived CDOM, enabling spatially explicit characterisation of carbon-related WQ dynamics.

4.4.1 Integrated water quality and anthropogenic pressure indices: WQI and ALCI [Paper III]

A weighted WQI was developed to synthesise multiple physicochemical and nutrient parameters into a single, normalised indicator of surface water condition. Individual parameters were first standardised using observed minimum values and maximum permissible limits defined by Bolivian national regulations (Congreso Nacional de Bolivia, Ley N°1333, 1992) and complementary international guidelines (GB3838-2002: Environmental Quality Standards for Surface Water, 2002; World Health Organization (WHO), 1998), following principles analogous to

the National Sanitation Foundation WQI framework (R. M. Brown et al., 1970). Parameter weights were objectively derived using principal component analysis (PCA), allowing variables with greater explanatory power to contribute more strongly to the index (Gazzaz et al., 2012). The weighted parameters were aggregated by summation, producing WQI values ranging from 0 to 1, which were classified into adapted qualitative categories from very poor to excellent WQ.

To explore temporal variability, seasonal WQI patterns were analysed using both spatial visualisation and non-parametric statistical testing. Given the non-normal distribution of most WQ variables, seasonal differences were evaluated using the Kruskal-Wallis test (Kruskal & Wallis, 1952). Data normality, pairwise differences, and monotonic associations were assessed using Shapiro-Wilk, Wilcoxon rank-sum, and Spearman correlation tests, respectively, implemented in R (Hollander & Wolfe, 1973; R Core Team, 2023; Royston, 1982). These analyses allowed detection of non-linear and scale-dependent relationships that are common in fluvial systems.

In parallel, the ALCI was developed to represent cumulative human pressure within the landscape. The index was calculated by summing the proportional coverage of human-modified LULC classes and normalising the result to a 0-1 range. ALCI was designed as a simplified, scalable metric that can be readily derived from RS-based LULC classifications, enabling consistent comparison across sites and time periods. The relationship between anthropogenic pressure and WQ was evaluated through Spearman correlations across multiple spatial configurations, including catchment, riparian, reach-scale, and accumulated upstream scenarios. This multi-scale framework allowed assessment of how spatial proximity and landscape aggregation influence WQ responses.

4.4.1 Trophic and carbon-related indicators: TSI and DOC [Paper IV]

Trophic conditions were quantified using the Carlson TSI, calculated for each sampling event and extended spatially through RS-based predictions. TSI was primarily derived from Chl-*a* concentrations using the classical logarithmic formulation (Carlson, 1977), and where Secchi disk depth data were available, a transparency-based TSI was additionally computed. Trophic states were classified into adapted categories ranging from ultra-oligotrophic to hypereutrophic conditions. Spatially explicit RS-based TSI maps were generated by applying the TSI formulation pixel-wise to the best-performing Chl-*a* prediction models and aggregating results at the lake scale to derive mean conditions and within-lake variability.

Modelled RS-TSI values were evaluated against indices computed from *in situ* observations using goodness-of-fit metrics, including R^2 , RMSE, and bias. Non-parametric paired Wilcoxon signed-rank tests were further applied to assess whether differences between observed and modelled lake-level means were statistically

significant, ensuring consistency between field-based and remotely derived trophic assessments.

DOC concentrations were estimated empirically using absorption coefficients of CDOM at 254 and 350 nm. A multiple linear regression model was calibrated using a subset of samples with concurrent DOC measurements, and model robustness was evaluated through leave-one-out cross-validation. Performance diagnostics included R^2 , RMSE, and residual analyses, complemented by Durbin–Watson and Breusch–Pagan tests to verify independence and homoscedasticity of residuals (Breusch & Pagan, 2008; Durbin & Watson, 1951). The best-performing CDOM products derived from Sentinel-2 imagery were subsequently used to generate spatially continuous DOC maps, which were summarised at the lake scale and compared with field observations to assess predictive accuracy and spatial variability.

4.5 Ecosystem services assessment and valuation [Paper V]

The ES modelling and valuation approach implemented in this study builds directly upon the empirical knowledge, RS outputs, and spatial analyses developed in Papers I–IV, complemented by global datasets and geographic analysis. Hydrological, WQ, were integrated with landscape, climatic, and socio-economic variables to support a multidimensional ES assessment. This integrative approach enabled the linkage of biophysical ES supply with accessibility, exposure, and human valuation, moving beyond single-discipline analyses. By combining spatially explicit modelling (InVEST), ML processes, landscape structure, and human perceptions, providing a comprehensive basis for assessing freshwater ES under heterogeneous environmental and social conditions.

4.5.1 Biophysical ecosystem service modelling (InVEST)

The biophysical supply of freshwater ES was quantified using the InVEST modelling suite. Seasonal water yield, nutrient delivery ratio, sediment delivery ratio, and carbon storage models were applied to characterise hydrological regulation, water purification, erosion control, and carbon pools across catchments, respectively. Model inputs incorporated climate variables, LULC, soil properties, and topographic information, ensuring spatially explicit representation of ES supply.

To complement biophysical outputs, spatial accessibility and exposure were characterised using geographic indicators, including distance to lakes, streams, *bofedales*, wells, and tree cover, as well as elevation, slope, TWI, and population

density. These variables provided a spatial link between ES supply and potential beneficiaries.

Table 2. Overview of InVEST ecosystem service models applied in this study, including their description, key outputs, and corresponding references			
Module	Description	Outputs	References
Seasonal water yield	Estimates seasonal water flow by partitioning precipitation into runoff and baseflow using a water balance approach, based on climate data, soil properties, topography, and land use/land cover	B, CN, L_avail, QF, Vri	Allen et al., 1998; Guswa et al., 2018; Hamel et al., 2020; Natural Resources Conservation Service, 2007
Nutrient delivery ratio	Estimates nutrient export using mass balance and flow routing, combining land use, nutrient loading rates, topography, and runoff to quantify nitrogen and phosphorus delivery to streams	Load_N, Load_P, N_total_exp, P_total_exp, NDR_N, NDR_P	California Regional Water Quality Control Board, Central Coast Region, 2013; Endreny and Wood, 2003; Heathwaite et al., 2005; Keeler et al., 2012; Reckhow et al., 1980; Redhead et al., 2018
Sediment delivery ratio	Estimates soil erosion and sediment export using the RUSLE and a connectivity index, based on rainfall, soil erodibility, topography, and land cover to model sediment delivery to streams	avoi_ero, avoi_exp, sed_export, RKLS, USLE	Bhattarai and Dutta, 2006; Borselli et al., 2008; Food and Agriculture Organization of the United Nations, 2006; Hamel et al., 2015; Merritt et al., 2003; Pelletier, 2012; Renard et al., 1997; Renard and Freimund, 1994
Carbon storage	Estimates carbon stocks by summing four carbon pools using land use/land cover maps and carbon density values, applying a lookup-table approach to quantify spatial carbon storage	C	Natural Capital Project, 2018 Intergovernmental Panel on Climate Change, 2006; Lal, 2004; Nelson et al., 2009; Stern, 2007; Tiessen et al., 1998; Zhang and Justice, 2001

Model validation focused on assessing consistency between modelled outputs and independent observations. Precipitation and reference evapotranspiration (ET₀), key climatic drivers in the InVEST framework, were evaluated against measurements from six meteorological stations. In addition, modelled exports of carbon (C), nitrogen (N), and phosphorus (P) were compared with concentrations measured in water samples collected at the outlets of 5-10 catchments. Spearman correlation analysis was used to assess the strength and direction of modelled-observed relationships, with statistical significance evaluated using *p*-values to ensure robustness of the validation results.

4.5.2 Socio-economic valuation based on non-market values

Socio-cultural valuation of freshwater ES was assessed using survey-based perceived importance scores for 24 services, measured on a five-point Likert scale, together with a set of 33 explanatory variables (Table 3), including geographic and socioeconomic factors and outputs from the biophysical ES assessment. These perceived importance variables were transformed into binary outcomes to examine how ES values emerge from interactions between environmental conditions, spatial context, and socio-economic characteristics. Instrumental valuation was represented by respondents' willingness to pay for ES, while relational valuation was captured through willingness to participate in environmental activities. Both were modelled as behavioural outcomes. Also socio-cultural valuation was assessed based on perceptions about ES importance.

Nr	Variable	Description	Category	Type
1	Age	Age of respondent (years)	Socio-demographic	Integer (years)
2	Agri	Engagement in agricultural activities (0 No, 1 Yes)	Socio-economic	Binary
3	avoi_ero	Avoided soil erosion	Erosion regulation (InVEST)	Continuous
4	avoi_exp	Avoided sediment export	Erosion regulation (InVEST)	Continuous
5	B	Baseflow	Hydrological (InVEST)	Continuous
6	C	Carbon storage or carbon density	Biophysical (InVEST)	Continuous
7	CN	Curve Number (runoff potential indicator)	Hydrological	Continuous
8	Dist_bofed	Distance to bofedales (high-Andean wetlands)	Spatial hydrological	Continuous
9	Dist_Lakes	Distance to lakes	Spatial hydrological	Continuous
10	Dist_river	Distance to rivers or streams	Spatial hydrological	Continuous
11	Dist_Treec	Distance to tree cover or forest patches	Landscape	Continuous
12	Dist_well	Distance to groundwater wells	Spatial hydrological	Continuous

Table 3. Socio-economic, spatial, hydrological, nutrient, and erosion-related variables included in the machine-learning models for freshwater ecosystem services valuation.

13	Edu	Education level of respondent (0 no studies - 5 postgraduate)	Socio-demographic	Categorical
14	Elev	Elevation (m above sea level)	Topographic	Continuous
15	L_avail	Local water availability (water yield)	Hydrological (InVEST)	Continuous
16	Lab_cat	Labour category or employment status (1-12)	Socio-demographic	Categorical
17	Load_N	Nitrogen load	Water quality (InVEST)	Continuous
18	Load_P	Phosphorus load	Water quality (InVEST)	Continuous
19	N_total_exp	Total nitrogen export	Water quality (InVEST)	Continuous
20	NDR_N	Nitrogen delivery ratio	Water quality / Nutrient transport (InVEST)	Continuous
21	NDR_P	Phosphorus delivery ratio	Water quality / Nutrient transport (InVEST)	Continuous
22	P_total_exp	Total phosphorus export	Water quality (InVEST)	Continuous
23	pop_ha	Population density (inhabitants per hectare)	Socio-demographic / Spatial	Continuous
24	QF	Quickflow (surface runoff component)	Hydrological (InVEST)	Continuous
25	RKLS	Rainfall erosivity-soil erodibility-topographic factor (USLE components)	Erosion modelling (InVEST)	Continuous
26	sed_export	Sediment export	Erosion / Hydrological (InVEST)	Continuous
27	Sew	Sewage system availability (1 public network - 5 open field)	Socio-environmental	Categorical
28	Slope	Terrain slope (degrees)	Topographic	Continuous
29	Sx	Sex of respondent (0 male, 1 female)	Socio-demographic	Binary
30	TWI	Topographic Wetness Index	Topographic / Hydrological	Continuous

Table 3. Socio-economic, spatial, hydrological, nutrient, and erosion-related variables included in the machine-learning models for freshwater ecosystem services valuation.				
31	USLE	Universal Soil Loss Equation output (estimated erosion)	Erosion modelling (InVEST)	Continuous
32	Vri	Recharge contribution index	Hydrological (InVEST)	Continuous
33	Wpro	Access to potable water (1 public network - 5 stream)	Socio-environmental	Categorical

XGBoost and RF classifiers were employed to model valuation outcomes, as these algorithms are well suited to capturing nonlinear relationships, interactions among predictors, and multicollinearity within heterogeneous datasets. The data were divided into independent training and validation subsets using stratified random sampling to preserve class proportions, while class-imbalance weighting was applied during model training to reduce bias associated with unequal response frequencies. Model hyperparameters were optimised through grid-based cross-validation, tuning parameters such as tree depth, number of estimators, learning rate, and subsampling ratios to improve generalisation and minimise overfitting.

Model performance was evaluated using complementary metrics, including overall accuracy, F1-score, and the ROC-AUC. Variable importance was first assessed using model-based importance measures to identify key socio-economic, environmental, and ES-related drivers. To enhance interpretability, SHAP were applied to quantify both the magnitude and direction of predictor contributions at individual and global scales (Lundberg & Lee, 2017). SHAP analysis enabled consistent comparison of drivers across models, revealing how biophysical ES supply, spatial accessibility, and social factors jointly shaped perceived importance, willingness to pay, and willingness to participate in freshwater ES management. Data preprocessing, statistical analyses, and modelling were conducted using Python (v3.11.4) and open-source libraries.

4.6 Framework integration and analytical workflow

This thesis advances beyond the individual contributions of Papers I–IV by integrating their data, methods, and outputs into a single, integrated analytical framework for freshwater ES assessment and valuation (Fig. 4). Rather than treating WQ, TSI, DOC, LULC, or ES as isolated components, the framework explicitly links biophysical processes, spatial patterns, and socio-economic responses across scales. This integration constitutes the core novelty of the research: it transforms heterogeneous datasets and disciplinary methods into an operational, spatially

explicit system capable of supporting both scientific understanding and decision-relevant insights, for water resources governance.

4.6.1 Data Flow

Data flow and analytical logic follow a structured sequence from observation to valuation (Fig. 4). Primary inputs include *in situ* WQ measurements (e.g. physicochemical parameters, Chl-*a*, CDOM, DOC, Secchi depth), satellite-derived optical products (Sentinel-2 and Landsat-8&9), hydroclimatic variables (precipitation, ET_o), LULC, topography, and socio-economic survey data. These inputs are first transformed through statistical and ML models to generate intermediate indicators: WQI, land use pressure metrics (ALCI), spatially continuous in-lake estimates of RS-TSI and DOC, and catchment-scale hydroclimatic and landscape descriptors. In a second transformation stage, primary inputs feed into ES modelling (InVEST) to quantify biophysical service supply (water yield, nutrient and sediment retention, carbon storage), as well as accessibility and exposure metrics derived from geographic analysis. Final outputs include spatially explicit ES supply maps (from InVEST), validated biophysical indicators, and ML-modelled socio-cultural, instrumental, and relational values of freshwater ES. This stepwise flow ensures traceability from raw observations to integrated ES valuation outcomes.

4.6.2 Scales

Scale integration is a defining feature of the framework. Papers I and II delineated a continental scale framing for characterise and contextualise Andean lakes in a spatially explicit regionalisation, exploring relevant hydroclimatic and topographic variables along with natural and anthropogenic stressors. Papers III-V contributed with local-scale measurements (sampling points, lake pixels, household surveys) are upscaled using RS, ML, and spatial aggregation to generate lake-, catchment-, and regional-scale indicators. Conversely, global and regional datasets (e.g. climate reanalysis, hydroclimate products, population grids) are downscaled and contextualised through catchment delineation, riparian buffers, and reach-scale analyses. This bidirectional scaling enables consistent linkage between processes operating at different spatial extents: optical WQ gradients within lakes, land use pressures across catchments, and socio-economic drivers operating at community and regional levels. Importantly, the framework produces spatially explicit outputs at resolutions relevant for management, while remaining compatible with broader comparative and global ES assessments.

4.6.3 Synthesis

Feedbacks and internal coherence further distinguish the framework from a linear aggregation of methods. ES valuation results provide feedback on the relevance and weighting of biophysical indicators, highlighting which aspects of WQ, hydrological regulation, or landscape condition are most influential for perceived importance, willingness to pay, or participation. These insights inform the interpretation of indices such as WQI, ALCI, and RS-TSI, revealing their societal relevance rather than treating them solely as environmental diagnostics. Similarly, discrepancies between modelled ES supply and observed or perceived values help identify scale mismatches, data gaps, or context-dependent relationships, reinforcing the iterative nature of the framework. In this way, valuation is not an endpoint but an interpretative layer that links ecological functioning to human decision-making.

Overall, the integrated framework delivers added value by (i) connecting classical and novel indicators with spatially explicit ES modelling, (ii) embedding RS-based WQ assessment within a socio-ecological valuation context, and (iii) enabling cross-scale synthesis that individual papers alone could not achieve. This coherence directly supports the novelty claim articulated at the outset of the thesis.

4.6.4 Methodological scope and limitations

The framework is designed to balance generality and context specificity, but several constraints should be acknowledged. Model performance depends on data availability and quality, particularly for carbon, nutrients, and sediment calibration, and socio-economic qualitative methods. InVEST models provide simplified representations of complex hydrological and biogeochemical processes, and valuation models capture associations rather than causality. Spatial and temporal mismatches between datasets may introduce uncertainty, especially when integrating seasonal field data with multi-year satellite products. These limitations do not undermine the framework's integrative value but define the conditions under which results should be interpreted and transferred to other regions.

5 Results and discussion

This chapter presents and discusses the main results of the thesis, demonstrating how the proposed social-ecological knowledge integration framework advances the understanding of freshwater systems in the study area and supports ES valuation and evidence-based water governance. By integrating global datasets, RS-derived WQ indicators, machine learning modelling, field observations, and socio-economic perceptions, the findings collectively address the thesis aim of linking biophysical processes with human dimensions across multiple spatial and organisational scales in data-scarce mountain environments.

The chapter first characterises Andean lakes, identifying key physical and ecological patterns, major threats, and persistent data gaps. It then examines how LULC dynamics influence WQ in streams along strong altitudinal gradients, before exploring trophic state, optical properties, and carbon dynamics in SHAL as emergent outcomes of catchment and climatic controls. Finally, the results incorporate social perceptions of freshwater ES, highlighting convergences and mismatches between biophysical conditions, stakeholder values, and management priorities. Together, these results provide an integrated, cross-scale interpretation of Andean freshwater systems, reinforcing the transdisciplinary and applied nature of the framework proposed in this thesis.

5.1 Andean lakes characterisation, threats and data gaps - [Papers I-II]

High Andean lakes constitute one of the most extensive yet least integrated freshwater systems globally, providing essential ES such as water supply, food provision, climate regulation, cultural values, and biodiversity support to millions of people across the Andes (Wittmann et al., 2015). Despite their ecological and socio-economic importance, Andean lakes have historically been studied in a fragmented manner, often at local scales and with limited comparability across regions, altitudinal gradients, and socio-environmental contexts. This lack of a system-wide perspective constrains the development of baseline knowledge required for effective monitoring, conservation, and governance, particularly under accelerating climate change and land use pressures.

This subsection addresses a central problem tackled in this thesis: the absence of an integrated characterisation of Andean lakes that simultaneously captures their spatial organisation, dominant physical features, major threats, and critical data gaps.

5.1.1 Key results: spatial organisation, dominant features, and main threats

Across the entire Andes Cordillera, lake size distribution is strongly skewed toward small systems. Numerically, the lake assemblage is dominated by lakes smaller than 10 km², which represent the vast majority (97%) of water bodies but contribute relatively little (13%) to the total surface area. In contrast, only nine very large lakes, primarily located in the Central and Southern Andes, account for most of the total lake area, highlighting a pronounced asymmetry between numerical abundance and spatial dominance. This pattern underscores the ecological relevance of small high-altitude lakes, which are numerous, widely distributed, and likely to be highly sensitive to environmental change, yet remain comparatively understudied.

Andean lakes were classified into eleven distinct lake districts spanning the Northern, Central, and Southern Andes (Figure 5a). These districts reflect coherent combinations of climatic, topographic, hydrological, and limnological characteristics, and their spatial configuration exhibits a strong and highly significant spatial autocorrelation (Global Moran's Index > 1 , $p < 0.001$). This result confirms that Andean lakes are not randomly distributed but instead organised into geographically and environmentally structured clusters, shaped by large-scale controls such as elevation, climate regimes, geological setting, and regional hydrology.

Beyond classification, the analysis revealed substantial asymmetries in data availability among lake districts. Limnological information is particularly scarce in several districts of the Central Andes, despite this region experiencing some of the strongest combined pressures from climate variability, water abstraction, and extractive activities. Long-term monitoring data are almost entirely absent across most districts, limiting the capacity to detect trends, attribute drivers of change, or anticipate future trajectories. These gaps highlight a critical imbalance between the ecological importance of Andean lakes and the scientific attention they have received.

The synthesis of ecological studies further demonstrates that Andean lakes are subject to multiple, interacting threats (Paper II). Key pressures include increased UVR (Häder et al., 2007), biological invasions by alien species (Arismendi et al., 2019), eutrophication and browning processes (Williamson et al., 2009), shifts in salinity and temperature driven by climate variability (Jeppesen et al., 2015), and mining-related impacts (Brain, 2017; Custodio, Álvarez, et al., 2020; Custodio, Chirinos, et al., 2020; Custodio, Cuadrado, et al., 2020; Gutierrez et al., 2022; Meza-

Duman et al., 2022). While some drivers, such as UVR and salinity changes, have a natural component, their intensity and ecological consequences are being amplified by anthropogenic activities, including atmospheric pollution and climate change. Other threats, such as nutrient enrichment, species introductions, and mining, are directly linked to land use change, population growth, and economic development along the Andes.

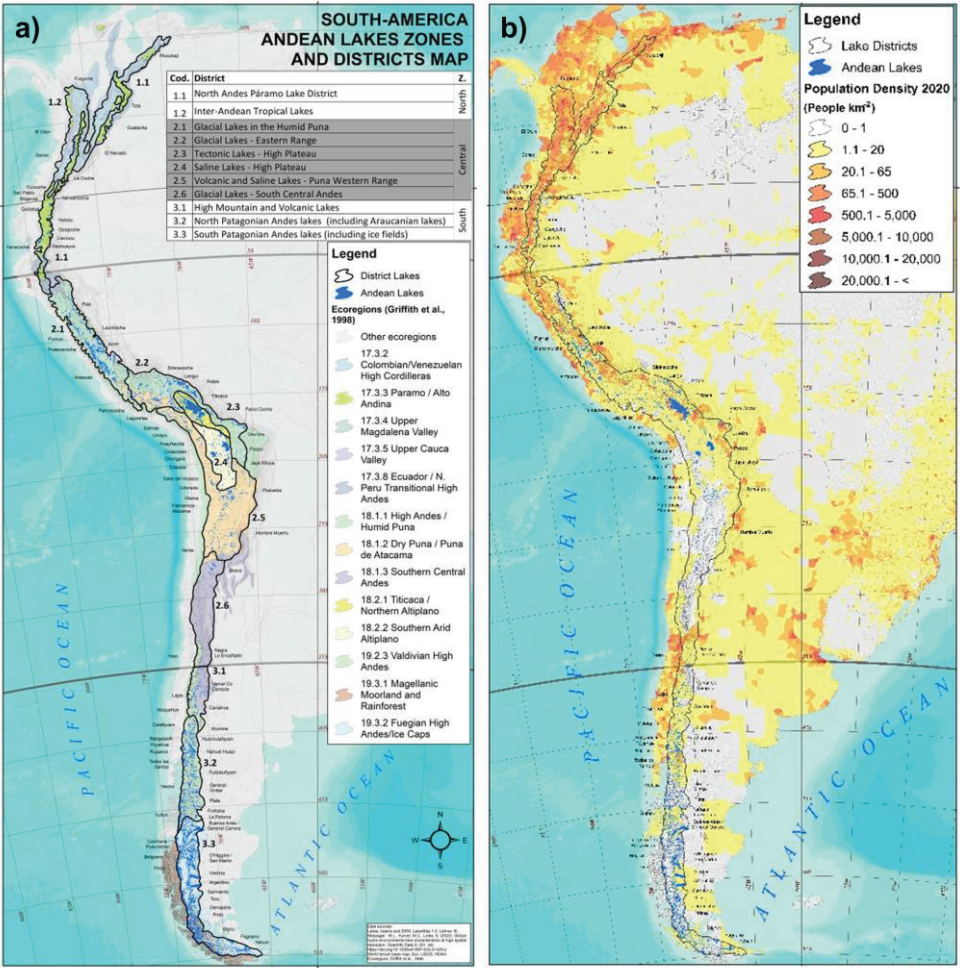


Figure 5. Andes Cordillera a) Lake districts, b) Population density. Figure from Papers I and II: Prado et al. (2024); Campero et al. (2024).

Notably, although much of the Andean Cordillera remains sparsely populated, human pressure is spatially concentrated in the Northern and Central Andes, where population density, agriculture, and mining activities are highest. This spatial

mismatch between low average population density and localised high-impact zones creates complex exposure patterns, where relatively remote lakes may still experience significant downstream or atmospheric influences. The expansion of mining activities, including lithium extraction in salt flats of Bolivia, Chile, and Argentina, represents a particularly acute risk, given the long water residence times of lakes and the limited understanding of contaminant accumulation and ecological responses in these systems (Gutierrez et al., 2022).

5.1.2 Interpretation and integration

Taken together, the results from Papers I and II shift the understanding of Andean lakes from isolated case studies toward a spatially structured, system-level perspective. The identification of lake districts provides a conceptual and analytical framework for comparing lakes with similar characteristics, enabling more targeted hypothesis testing, monitoring design, and management strategies. This approach aligns Andean lake research with global limnological efforts that emphasise typologies and regionalisation as prerequisites for scalable assessment and governance (Soranno et al., 2010).

At the same time, the synthesis of threats highlights that Andean lakes are embedded within tightly coupled social-ecological systems, where climatic drivers, land use change, and human activities interact across scales. The convergence of eutrophication, warming, salinisation, and biological invasions suggests that many lakes may be approaching ecological thresholds, beyond which ecosystem functioning and service provision could change abruptly (Scheffer et al., 2001). These findings reinforce global observations that freshwater biodiversity loss is occurring faster than in terrestrial or marine systems (Kuiper, 2023), while emphasising that Andean lakes may be particularly vulnerable due to their isolation, extreme conditions, and limited resilience.

Importantly, the results challenge the perception that remoteness equates to protection. Even lakes located in sparsely populated regions are increasingly exposed to diffuse pressures such as climate change, atmospheric deposition, and regional hydrological alteration. This insight underscores the need to move beyond local-scale assessments and adopt integrated, cross-scale perspectives when evaluating the status and future of mountain freshwater systems.

5.1.3 Implications and limitations: monitoring, remote sensing, and management relevance

The characterisation of Andean lake districts and the identification of major threats have direct implications for monitoring and management. The pronounced lack of long-term and spatially balanced limnological data limits the capacity of institutions to anticipate change, prioritise interventions, or evaluate the effectiveness of

conservation measures. In this context, RS and global datasets emerge as indispensable tools for reducing information asymmetries, enabling consistent baseline assessments across vast and inaccessible regions (Pekel et al., 2016; Topp et al., 2020).

However, the results also highlight key limitations. Satellite-based indicators and global databases cannot fully substitute for *in situ* observations, particularly for understanding biogeochemical processes, ecological interactions, and local socio-cultural dynamics. Data scarcity remains a structural constraint in mountain systems, driven by logistical challenges, financial limitations, and uneven research investment among countries and regions.

Many Andean lakes are already recognised for their ecological uniqueness and designated as protected or Ramsar sites (Wittmann et al., 2015), yet protection status alone is insufficient without sustained monitoring, integrated assessments, and governance mechanisms that account for cross-scale drivers. From a management perspective, the findings emphasise the urgency of proactive rather than reactive strategies. Addressing these challenges requires coordinated efforts combining limnology, RS, hydrology, social sciences, and policy, positioning Andean lakes as priority systems for transdisciplinary research and integrated sustainable water management.

5.2 LULC influence in stream water quality - [Paper III]

LULC change is a dominant driver of freshwater degradation worldwide, yet its effects remain poorly quantified in high Andean headwater systems, where strong altitudinal gradients, pronounced seasonality, and engineered hydrological alterations interact within complex hydro-social landscapes. In the Central Andes, streams draining small to medium-sized watersheds play a critical role in supplying water for domestic use, agriculture, energy production, and ecosystem functioning. However, these systems are increasingly exposed to agricultural expansion, urbanisation, and infrastructure development, often in the absence of sustained WQ monitoring and integrated watershed planning.

This subsection addresses the problem of how LULC composition and spatial configuration influence stream WQ in data-scarce Andean watersheds, and how this relationship varies across spatial scales and hydrological conditions. Drawing on Paper III, the analysis integrates open-access EO data processed in GEE (Gorelick et al., 2017), multiscale spatial scenarios, field-based WQ measurements, and both statistical and ML models. Two representative Andean watersheds with contrasting gradients and altered hydraulic configurations, due to inter-basin water transfers through tunnels and channels, are examined. By explicitly accounting for seasonality, scale, and non-linear relationships, this subsection contributes empirical evidence to a key objective of the thesis: how catchment-scale human pressures

propagate through stream networks and affect WQ and related ES, and how RS-based approaches can support evidence-based, ecosystem-oriented water governance in mountain regions.

5.2.1 Key results: hydrological alteration, scale dependence, and dominant LULC drivers

Results indicate that streamflow and WQ dynamics in the studied watersheds are strongly influenced by anthropogenic hydrological modifications. Since 2018, water discharged from a hydropower plant has become a major component of streamflow, particularly during the dry season, when turbinated water accounted for up to 69-94% of total discharge in the two watersheds, respectively. Even during the wet season, this additional input represented a substantial fraction of streamflow. This artificial dilution effect played a significant role in moderating pollutant concentrations, highlighting how engineered water transfers may obscure or alter relationships between LULC and WQ if not explicitly considered.

Across spatial scenarios and seasons, a strong inverse relationship emerged between the ALCI and the WQI, particularly during the wet season (Figure 6). Higher proportions of anthropogenic LULC were consistently associated with poorer overall WQ, while higher precipitation enhanced runoff and transport processes, strengthening the LULC signal during high-flow conditions. In contrast, during the dry season, significant relationships were mainly observed at the catchment and riparian scales, reflecting reduced hydrological connectivity and a stronger influence of local sources.

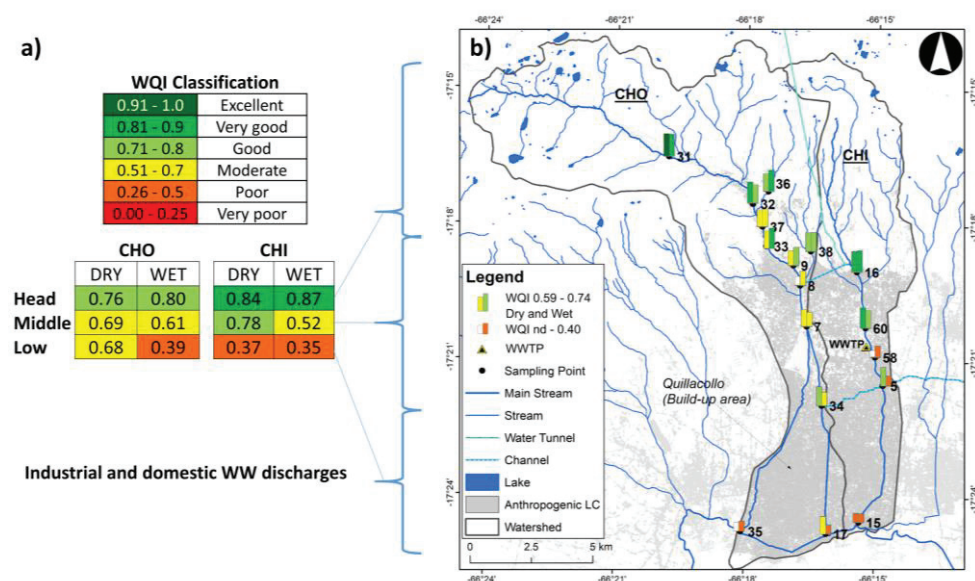


Figure 6. Water quality index (WQI) and Anthropogenic Land Cover Index (ALCI). a) WQI classification and values, adapted from NSF WQI (Brown et al, 1970). b) WQI distribution over the studied streams and ALCI as background. WW: wastewater; WWTP: wastewater treatment plant. Figure from Paper III: Prado et al. (2025)

ML models, particularly RF regression, outperformed PLSR in capturing the complex, non-linear relationships between LULC and individual WQ parameters. RF regression achieved very high predictive performance for key pollution indicators, including total coliforms, thermotolerant coliforms, metals, total solids, turbidity, and the composite WQI, with coefficients of determination exceeding 0.9 in the most representative spatial scenarios. PLSR showed lower but still meaningful performance, indicating that linear approaches capture part of the signal but underestimate interactions and thresholds inherent to coupled land-water systems.

Spatial scale emerged as a critical determinant of model performance and interpretation. Accumulated catchment-based scenarios and catchment percentage metrics consistently explained the largest proportion of variance in WQ parameters and WQI, confirming that upstream land use composition exerts a dominant control on stream condition. Riparian and reach-scale scenarios, while less influential overall, were particularly relevant for parameters such as pH and sediment-related variables, emphasising the buffering and filtering role of riparian vegetation.

Across both modelling approaches, anthropogenic LULC classes, especially built-up areas, cropland, and lawn, were identified as the most influential contributors to WQ degradation. These LULC showed strong associations with nutrient enrichment, microbial contamination, and increased solids. In contrast, natural land covers such as grassland, wetlands, tree cover, and rocky areas were generally associated with improved WQ, particularly at riparian and reach scales. Average precipitation also emerged as an important predictor, although its relative importance was consistently lower than that of anthropogenic LULC. Together, these variables explained more than 60% of WQ variability based on variable importance metrics. This reinforces the primacy of land use management over climatic variability in shaping WQ patterns at the watershed scale.

5.2.2 Interpretation and integration

The results from Paper III provide clear evidence that stream WQ in Andean headwaters is shaped by a combination of land use composition, spatial scale, seasonality, and hydrological alteration. The observed increase in anthropogenic LULC between 2016 and 2024, reflected in a rising ALCI, aligns with broader regional trends of agricultural intensification and urban expansion in the study area. The strong, negative relationship between ALCI and WQI suggests that integrated

LULC indicators can serve as cost-effective proxies for overall stream condition in similar environmental contexts, particularly where field monitoring is limited.

The superior performance of RF regression compared to PLSR confirms that LULC-WQ relationships are inherently non-linear and multidimensional, a finding consistent with recent studies applying ML to WQ prediction in other regions (Krishnaraj & Honnasiddaiah, 2023; Venkateswarlu & Anmala, 2024; Z. Zhang et al., 2022). Importantly, both modelling approaches converged on similar conclusions regarding the dominant role of anthropogenic LULC and the relative importance of catchment-scale processes, lending robustness to the findings.

These results are consistent with a growing body of literature showing that catchment-scale LULC patterns often exert stronger controls on WQ than local-scale metrics (Mello et al., 2018, 2020; Tanaka et al., 2016), while riparian buffers play a critical mitigating role under certain climatic and geomorphic conditions (Paná et al., 2024; Shi et al., 2017). In the Andean context, the interaction between steep topography, episodic rainfall, and fragmented natural vegetation likely amplifies the transmission of pollutants from source areas to stream networks.

By explicitly incorporating altered hydrological regimes due to inter-basin transfers, this study also challenges the assumption that observed WQ patterns solely reflect natural hydrological variability. Instead, it highlights how hydro-social infrastructures can reshape biophysical signals, in line with hydro-landscape co-evolution, complicating attribution and management unless such interventions are explicitly accounted for.

5.2.3 Implications and limitations: monitoring, remote sensing, and watershed management

The findings have important implications for monitoring and management of Andean headwater streams. First, they demonstrate the potential of integrating RS, open-access data, and ML to assess WQ drivers in regions with sparse historical records. This approach provides a scalable and cost-effective pathway for identifying priority areas, evaluating land use impacts, and supporting ES oriented decision-making.

Second, the results underscore the necessity of adopting a multiscale perspective in watershed management. Policies focused exclusively on riparian buffers or point-source controls may be insufficient if catchment-scale land use pressures continue to intensify. Instead, integrated strategies that balance agricultural production, urban development, and the conservation of natural land covers are required to safeguard WQ-related ES.

Several limitations remain. The complexity of landscape composition and configuration was only partially captured using LULC proportions, and future work could benefit from incorporating landscape metrics and “source-sink” concepts to better represent pollutant generation and attenuation processes (L. Chen et al., 2008;

Y. Wang et al., 2021). Moreover, physicochemical indicators alone provide an incomplete picture of ecological integrity. Integrating biological assessments, such as macroinvertebrate or periphyton-based indicators (Gordon et al., 2004), would strengthen understanding of ecosystem responses to LULC pressure.

Data scarcity remains a fundamental constraint in Andean watersheds, particularly regarding long-term WQ records and historical LULC maps (Gestión Integral del Agua Cochabamba, GIAC, GADC, 2019). Nonetheless, the optimised workflow developed in this study demonstrates how methodological integration can partially overcome these limitations, offering transferable tools for similar mountain basins facing rapid environmental change.

5.2.4 Synthesis and policy relevance

Overall, this subsection demonstrates that LULC exerts a strong, scale-dependent influence on stream WQ in Central Andean headwaters, with anthropogenic LULC consistently associated with degradation and natural land covers providing critical buffering functions. The multiscale, ML-enabled framework developed in Paper III not only advances scientific understanding of LULC-WQ linkages but also delivers actionable insights for integrated water resources management. By supporting evidence-based policies aligned with the Sustainable Development Goals, particularly those related to water, land use, climate adaptation, and biodiversity, these results reinforce the value of combining EO, modelling, and field data to inform sustainable governance in complex mountain socio-ecological systems.

5.3 Trophic state, optical properties, and carbon dynamics in SHAL - [Paper IV]

SHAL of the Central Andes are ecologically sensitive systems that provide essential ES, including drinking water supply, food provisioning, biodiversity support, and carbon storage. Their remote location, strong climatic forcing, and limited monitoring infrastructure have resulted in major knowledge gaps regarding trophic state dynamics, organic matter accumulation, and early signals of WQ degradation. In this context, the ability to monitor lake productivity and carbon pools using cost-effective and scalable approaches is critical for sustainable water management in mountain regions.

This subsection addresses how RS-based optical indicators, when integrated with landscape structure and hydroclimatic variability, can be used to assess trophic state and carbon dynamics in SHAL. Drawing on Paper IV, the analysis moves beyond lake-scale description by explicitly linking satellite-derived proxies (Chl-*a*, transparency, turbidity, and CDOM) with catchment attributes, elevation gradients,

and lagged precipitation signals. The study focuses on SHAL in glacial lakes of the Eastern Range District, part of the Bolivian Central Andes (Prado et al., 2024).

5.3.1 Key results: optical retrievals, trophic gradients, and carbon pools

Overall, the results demonstrate that satellite-based models can robustly retrieve key optical and biogeochemical indicators across SHAL when spectral information is combined with landscape and hydrological descriptors. Across both Landsat OLI and Sentinel-2 MSI sensors, model performance improved markedly after integrating indices sensitive to phytoplankton pigments and suspended matter with elevation, *bofedales* coverage, ALCI, and antecedent precipitation. Sentinel-2 MSI consistently outperformed Landsat OLI for Chl-*a*, transparency, and CDOM, while Landsat showed strong performance for turbidity, reflecting differences in spatial resolution, spectral configuration, and sensor sensitivity (Figure 7).

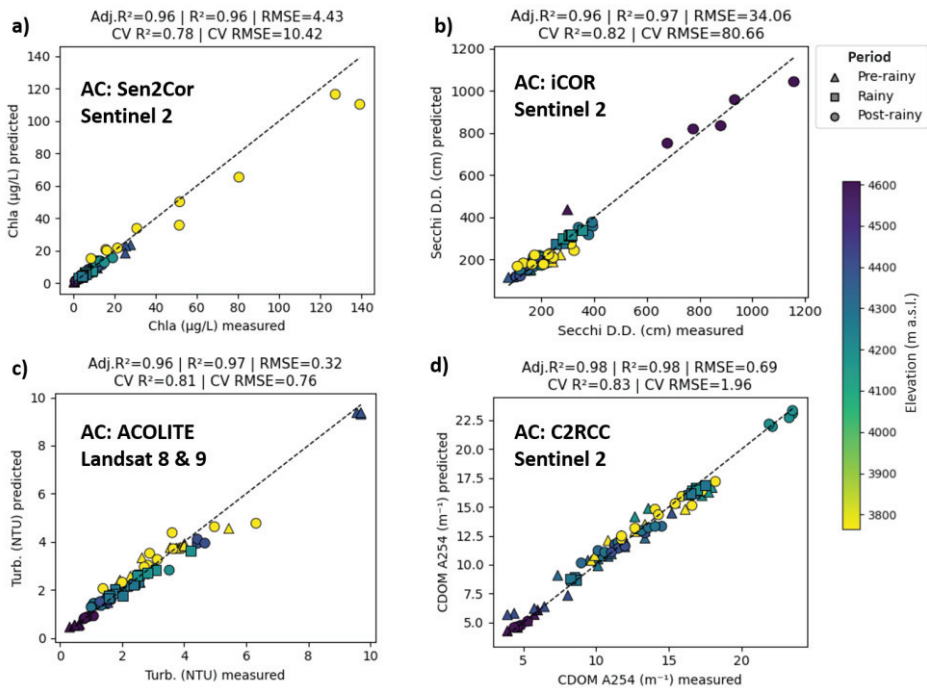


Figure 7. Scatter plots of the best-performing models for each parameter: a) Chl-a, b) Transparency, c) Turbidity, and d) CDOM a254. Marker colour represents elevation (lighter tones = lower elevations; darker tones = higher elevations), while marker shape indicates period (triangles = pre-rainy, squares = rainy, circles = post-rainy). Figure from Paper IV: Prado et al. (2026).

Spatial predictions revealed ecologically coherent patterns across the lake system. Elevated Chl-*a*, turbidity, and CDOM concentrations were consistently observed near inflow zones, shallow margins, and *bofedales*-connected areas, while deeper pelagic zones exhibited higher transparency and lower optical complexity. Seasonal contrasts were pronounced: post-rainy conditions were associated with increased pigment concentrations and DOM, reflecting enhanced runoff, sediment mobilisation, and lake-catchment connectivity. These spatial and temporal patterns were statistically robust, with strong agreement between predicted and measured lake means and no evidence of systematic bias.

RS-derived Carlson TSI values showed strong agreement with *in situ* estimates based on measured Chl-*a*, confirming the reliability of the RS-based approach for trophic classification. The derived TSI effectively captured both spatial gradients linked to elevation and LULC, and seasonal shifts associated with hydrological forcing. DOC estimates showed moderate agreement with laboratory measurements, with higher uncertainty in highly altered systems, particularly the Misicuni reservoir, where DOC was consistently overestimated. Nevertheless, DOC predictions revealed clear spatial patterns, with higher concentrations in lakes surrounded by *bofedales* and cropland, and consistent post-rainy increases across the system.

5.3.2 Interpretation and integration: mechanisms, scales, and system behaviour

From a process perspective, these results highlight that trophic state and optical complexity in SHAL emerge from tightly coupled lake-catchment-climate interactions. Seasonality exerted a dominant influence, with increasing temperatures associated with lower dissolved oxygen and pH, and higher electrical conductivity due to evaporative concentration during dry periods (Servicio Nacional de Meteorología e Hidrología (SENAMHI), 2025). Similar seasonal controls have been documented in Andean and Patagonian lakes (Aguilar et al., 2018; Chanamé-Zapata et al., 2020; Huovinen et al., 2019), indicating that these mechanisms are widespread in high-altitude systems.

Catchment configuration further modulated these seasonal signals. Lakes draining *bofedales*-rich catchments consistently exhibited higher Chl-*a*, turbidity, and CDOM, particularly at lower elevations and under stronger anthropogenic pressure. *Bofedales* act as important sources of nutrients and organic matter, exporting dissolved carbon during and after rainfall events, thereby sustaining elevated DOC and CDOM concentrations (Aguilera et al., 2013; Van Colen et al., 2017). In contrast, high-elevation lakes embedded in rocky or grassland-dominated catchments showed lower trophic state, higher transparency, and reduced optical

complexity, reflecting limited nutrient availability and shorter hydrological residence times.

Strong correlations among DOC, CDOM, Chl-*a*, and antecedent precipitation support the interpretation that carbon pools in SHAL are regulated by both allochthonous inputs and in-lake primary production. This dual control aligns with findings from other Andean and Patagonian systems, where wetland extent, drainage development, and precipitation regimes jointly govern organic matter dynamics (Sánchez Valdivia et al., 2024). Transparency emerged as a potential integrative indicator, responding to biomass accumulation, suspended solids, and hydrological flushing, and thus providing a useful proxy for overall lake condition.

Differences among lake types further underscored the importance of morphometry and hydrological setting. Shallow systems exhibited higher turbidity and stronger vegetation influence, while deeper headwater lakes functioned as clearer reference systems. The Misicuni reservoir showed distinct behaviour, transitioning seasonally toward hypereutrophic conditions while maintaining relatively stable DOC concentrations, a pattern consistent with strong anthropogenic regulation and upstream organic matter loading. Similar morphometry-driven contrasts have been reported in Bolivian and Patagonian lakes (Aguilera et al., 2013; Sánchez Valdivia et al., 2024).

The DOC-CDOM empirical relationship developed in this study showed strong predictive capacity, consistent with relationships reported for natural waters globally (Brezonik et al., 2005; Fichot & Benner, 2011; Spencer et al., 2012). The inclusion of absorption coefficients at 254 and 350 nm enhanced sensitivity to aromatic and humic fractions of DOM, enabling spatial assessment of carbon pools linked to *bofedales* and agricultural influence. Although uncertainty remains, particularly in highly altered systems, these DOC estimates represent an important step toward quantifying carbon dynamics and associated ES in Andean lakes.

5.3.3 Implications and limitations

Despite strong model performance, several limitations should be acknowledged. Limited DOC calibration data constrain generalisation across the full range of optical conditions, while temporal mismatches between satellite acquisitions and field sampling introduce additional uncertainty. Mixed-pixel effects in small or irregularly shaped lakes and residual atmospheric correction biases remain persistent challenges. Nevertheless, the consistency of results across sensors, AC methods, and validation metrics suggests that the major spatial and seasonal patterns identified here are robust.

From a management perspective, the seasonal transition of the reservoir toward hypereutrophic conditions is of particular concern, given its role as the primary drinking water source for approximately one million inhabitants of the Cochabamba metropolitan area. These findings highlight the vulnerability of engineered Andean water systems to combined climatic variability and land use pressure, and

underscore the need to integrate watershed management with lake monitoring to safeguard WQ and ES.

Despite a growing body of research on zooplankton richness in high-altitude lakes of the central Andes (Acosta et al., 2022; Fernández et al., 2024; Quenta-Herrera et al., 2022; Quenta et al., 2016), these studies remain largely based on *in situ* observations and lack systematic integration with RS-WQ parameters. This disconnect limits the ability to assess ecological conditions across spatial and temporal scales, particularly in remote and data-scarce regions. Integrating biodiversity indicators with satellite-derived WQ parameters would provide a more comprehensive understanding of habitat conditions and ecosystem functioning. Such an approach is especially relevant for SHAL, which, despite their limited size, can serve as critical habitats supporting unique and sensitive biotic communities. Advancing this integration represents a key opportunity to improve ecological monitoring and to strengthen the role of these systems in regional biodiversity conservation strategies.

Overall, this study provides the first integrated, multi-sensor assessment of trophic state, optical properties, and carbon dynamics in SHAL of the Bolivian Central Andes. By combining multispectral satellite observations with landscape and hydroclimatic descriptors, it establishes a cost-effective and scalable framework for monitoring WQ, ecosystem condition, and carbon pools in remote mountain regions. The resulting RS-derived indicators create a direct link between biophysical lake processes and ES assessment, supporting ecosystem-based management, land use planning, and evidence-based decision-making under accelerating environmental change.

5.4 Social perceptions of freshwater ecosystem services - [Paper V]

Freshwater ES in the Andes are embedded in tightly coupled social-ecological systems, where biophysical processes, LULC change, institutional arrangements, and everyday practices co-evolve across scales. While previous sections of this thesis focused on characterising aquatic ecosystems and quantifying biophysical drivers of WQ and ecosystem functioning, sustainable water management ultimately depends on how these systems are perceived, valued, and governed by society. Integrating social perceptions into ES assessments is therefore not complementary but essential for translating scientific knowledge into actionable and legitimate decision-making.

This subsection addresses the social dimension of the integrated framework developed in this thesis by analysing community perceptions of the conservation status, importance, and value of freshwater ES in peri-urban Andean municipalities. Drawing on Paper V, it examines how socio-economic conditions, spatial proximity

to aquatic ecosystems, and environmental characteristics shape instrumental values (expressed as willingness to pay), relational values (expressed as willingness to participate in collective environmental actions), and socio-cultural values. In doing so, it operationalises the social-ecological systems perspective outlined in the theoretical background and directly contributes to the thesis aim of linking RS-based indicators, InVEST modelling outputs (Figure 8), and field data with socio-economic perceptions to support ES valuation and integrated water management.

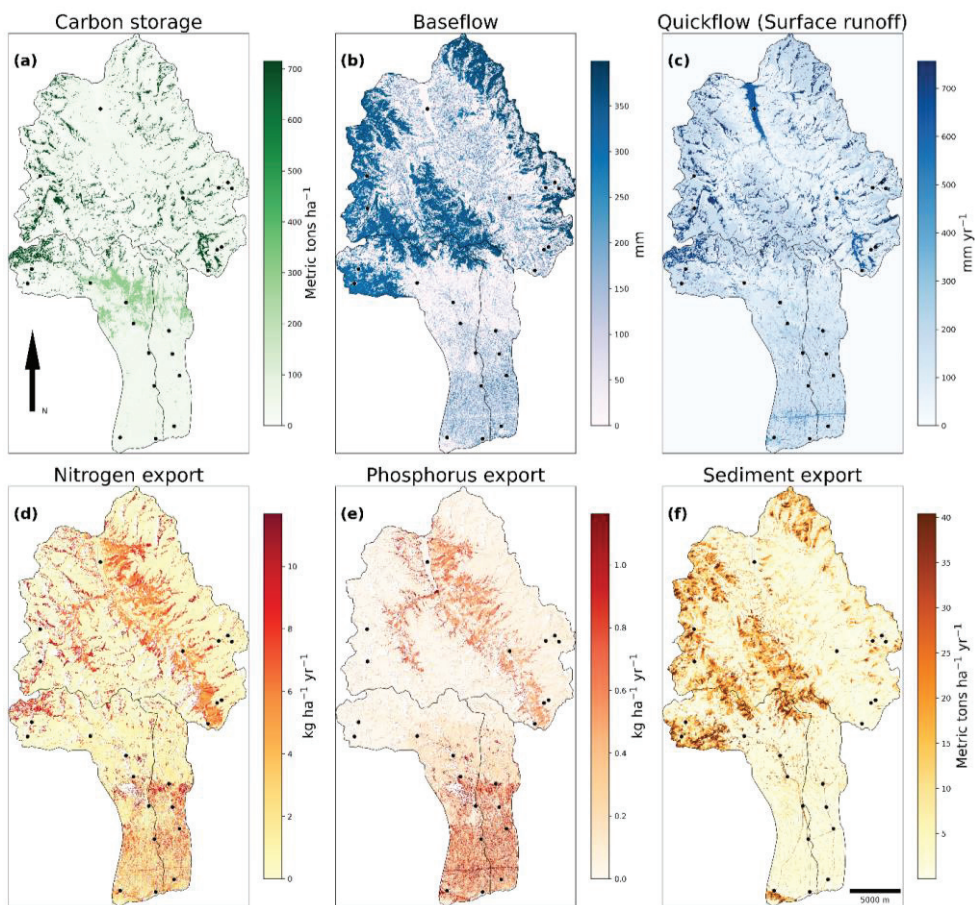


Figure 8. Key biophysical outputs from the InVEST modelling framework across the study catchments: (a) carbon storage ($\text{metric tons ha}^{-1}$), (b) baseflow (mm), (c) quickflow or surface runoff (mm yr^{-1}), (d) nitrogen export ($\text{kg ha}^{-1} \text{yr}^{-1}$), (e) phosphorus export ($\text{kg ha}^{-1} \text{yr}^{-1}$), and (f) sediment export ($\text{metric tons ha}^{-1} \text{yr}^{-1}$). Black lines represent the boundaries of the catchments, while black dots mark the locations where water samples were collected for model validation.

Figure from Paper IV: (Prado, Rejas, Oporto, Jönsson, Decsi, et al., 2026)

5.4.1 Socio-ecological context of water use and livelihoods

The surveyed population reflects the socio-economic heterogeneity and governance complexity typical of Andean peri-urban landscapes. Households are predominantly of working age, with moderate educational attainment and livelihoods centred on informal employment and small-scale agriculture. Agricultural practices are largely subsistence-oriented, relying heavily on irrigation water sourced from channels,

springs, streams, and wells, with rainfed production playing a limited role. Livestock production is similarly small-scale and spatially constrained.

Water access and sanitation conditions highlight the hybrid nature of water governance in the study area. Most households depend on self-organised systems managed by local associations or cooperatives, while municipal supply coverage remains limited. Household-level water storage is widespread, reflecting both infrastructural gaps and adaptive responses to water insecurity. These characteristics situate freshwater ecosystems not as distant environmental assets, but as directly experienced systems underpinning daily life, livelihoods, and well-being.

Environmental concerns expressed by respondents, particularly WQ degradation, waste accumulation in streams, and wildfire risk, mirror the biophysical pressures identified in earlier sections of this thesis through RS, modelling, and field measurements. Importantly, despite these pressures, respondents showed high willingness to engage in environmental activities (54%), participate in monitoring (93% at least once a year), and contribute financially to ES conservation (64%). This indicates substantial social capital and a favourable context for participatory and co-management approaches to water governance.

5.4.2 Perceived importance and condition of ecosystem services

Across all ES categories, a consistent and policy-relevant pattern emerged: perceived importance systematically exceeded perceived ecosystem condition, especially for regulating and supporting services. Services related to water regulation, erosion control, water purification, and habitat support were most frequently rated as very important, yet simultaneously perceived as being in degraded or declining condition. This mismatch reflects a socially perceived deficit between ecosystem performance and societal expectations, signalling priority areas for intervention (Figure 9).

Provisioning services displayed more heterogeneous perceptions. While services directly related to water availability and quality were highly valued, other provisioning services, such as river aggregate extraction or grazing resources, were often perceived as unimportant, reflecting their limited contribution to household well-being or their association with environmental degradation. Cultural ES exhibited a contrasting pattern, with perceived ecosystem condition slightly exceeding perceived importance. This suggests that while cultural benefits such as scenic beauty or recreational spaces are present and experienced, their societal relevance may be undervalued or taken for granted.

At the level of individual services, air quality regulation emerged as the most highly valued service, while extractive services associated with riverbeds consistently received the lowest importance scores. Spatial analysis revealed that perceived importance was relatively homogeneous across municipality districts, whereas perceptions of ecosystem condition showed less spatial variability,

suggesting shared understandings of environmental degradation across the study area.

The analysis of the relationship between perceived importance and perceived condition further highlighted moderate to low correlations for several regulating and supporting services (Fig. 9). Services combining high importance with low perceived condition (biodiversity, nutrient cycle, air quality, among others) represent critical leverage points for management and restoration, as they align strong social demand with perceived ecological decline. Conversely, services perceived as being in good condition but of low importance (spiritual beliefs, scenic beauty, groundwater quality, among others) may indicate gaps in awareness rather than ecological scarcity, pointing to opportunities for environmental education and communication.

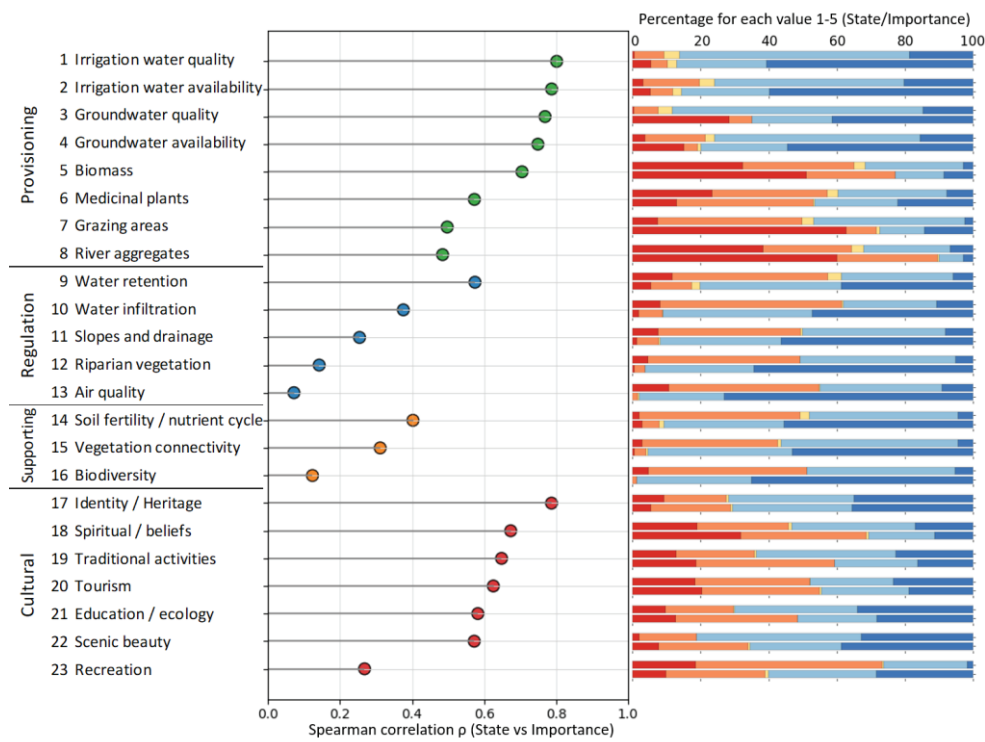


Figure 9. Spearman's correlation of state–importance for each ecosystem service by category (left). Proportional distributions of Likert responses for the perceived state (top bar) and importance (bottom bar) of ecosystem services. Each pair corresponds to one service measured using two survey items. Bars display the percentage of respondents selecting values from 1 to 5 on a 5-point Likert scale. Colours represent Likert categories (warm colours = 1 and 2, yellow = neutral (3), cold colours = 4 and 5). Figure from Paper IV: (Prado, Rejas, Oporto, Jönsson, Decsi, et al., 2026)

5.4.3 Instrumental and relational valuation within an integrated framework

To move beyond descriptive perception analysis, this study applied supervised machine learning approaches to model ES valuation, explicitly linking social responses with environmental and spatial indicators derived from the integrated framework developed in this thesis. Instrumental valuation was assessed through respondents' WTP, while relational valuation was captured through willingness to participate in environmental and ecosystem-related activities. This approach addresses limitations of conventional ES valuation methods, which often fail to capture non-linear interactions and spatially explicit socio-environmental dynamics (Costanza, 2020; Pandeya et al., 2016; Scowen et al., 2021).

The XGBoost models demonstrated stronger overall predictive performance for WTP (Accuracy = 0.73, F1 = 0.78, ROC–AUC = 0.81) compared to the RF classifier (Accuracy = 0.71, F1 = 0.80, ROC–AUC = 0.72), indicating improved discrimination between valuation responses. Key predictors included education level, water provision source, sanitation access, proximity to lakes and *bofedales*, erosion susceptibility, nutrient loads, elevation, and age. SHAP analysis further revealed that higher education, improved infrastructure, shorter distances to water bodies, and greater exposure to environmental pressures (e.g., erosion and nutrient export) increased the likelihood of positive WTP responses. These findings highlight that ES valuation reflects an integrated assessment of livelihood conditions, environmental exposure, and perceived ecosystem functionality, consistent with previous studies (Bassa, 2024; Pandeya et al., 2016).

Relational valuation models showed moderate but robust performance (Accuracy = 0.69, F1 = 0.69, ROC–AUC = 0.74), reflecting the more complex and context-dependent nature of participation. Engagement in environmental actions was influenced by proximity to lakes, *bofedales*, and streams, as well as hydrological and LULC characteristics, including CN, erosion control capacity, and carbon storage. Socioeconomic factors such as education, labour category, and age also played a significant role. Respondents located closer to water bodies and within catchments characterised by moderate hydrological regulation were more likely to participate, underscoring the importance of direct interaction with ecosystems in shaping relational values (Kadykalo et al., 2019; Tasser et al., 2025).

Overall, these results demonstrate that ES valuation is driven by a complex interplay of social, infrastructural, and environmental factors, and that ML approaches are well suited to capture these non-linear relationships (Scowen et al., 2021). Importantly, the combined analysis of instrumental and relational values reveals complementary dimensions of human-ecosystem interactions, reinforcing

the need to integrate economic and participatory perspectives to support socially legitimate and ecologically grounded conservation strategies.

5.4.4 Drivers of valuation across ecosystem service categories

A comparison between model-derived feature importance and aggregated SHAP metrics (Figure 10) indicates broad consistency in the identification of key drivers of ES valuation, while offering complementary interpretative perspectives. Both approaches emphasize the central role of spatial configuration, hydrological dynamics, and access to water and sanitation infrastructure. Variables such as proximity to lakes, *bofedales*, water accessibility, avoided erosion, carbon storage, distance to streams, along with elevation, CN, baseflow contribution, and distance to wells, highlight the importance of water infrastructure and catchment functioning. In contrast, socioeconomic characteristics such as agricultural engagement, sanitation access, age, and education exerted a more moderate yet consistent effect, indicating that social context mediates the translation of environmental conditions into perceived value.

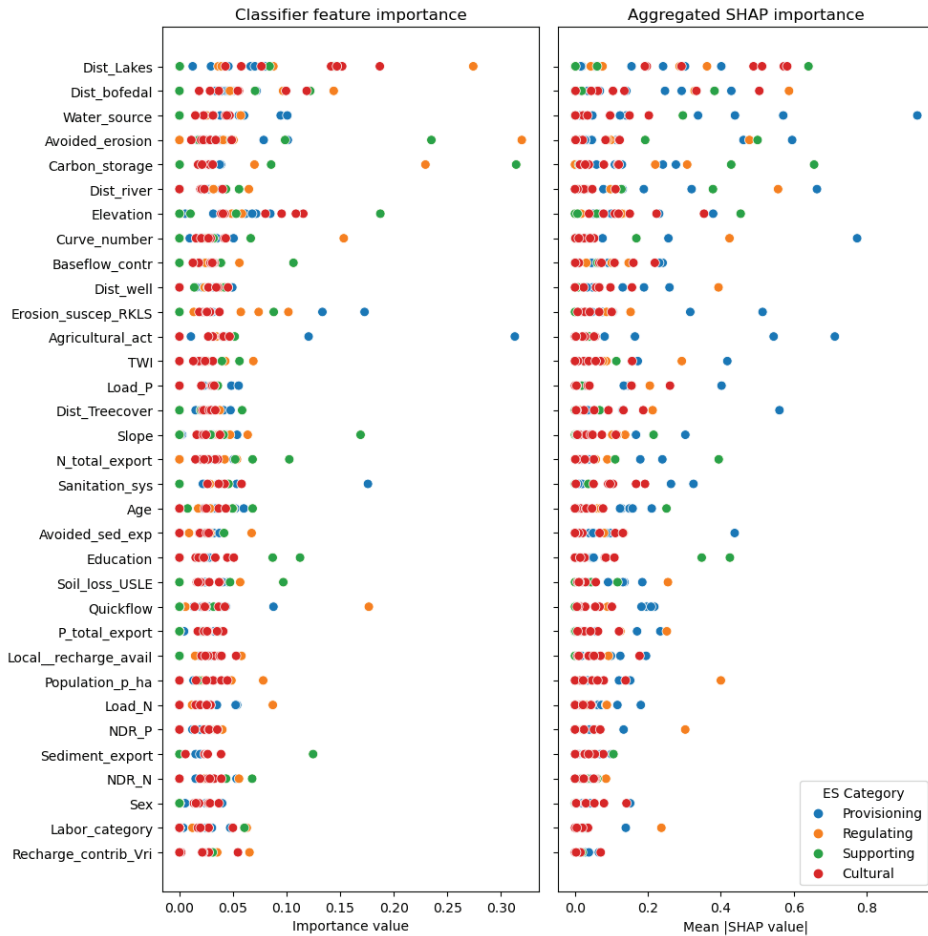


Figure 10. Comparison of classifier feature importance and aggregated SHAP importance. Features are ordered by aggregated SHAP importance (mean absolute SHAP value) and displayed in two panels: classifier-derived importance (left) and SHAP-based importance (right). Points are coloured by feature category, facilitating interpretation of the relative contribution of socio-economic, biophysical, and ES-related variables to model predictions. Figure from Paper IV: (Prado, Rejas, Oporto, Jönsson, Decsi, et al., 2026)

Model performance and predictor importance varied across ES types, revealing important insights for integrated management. Provisioning services related to water availability and quality exhibited the strongest predictive performance, reflecting their direct relevance to household well-being and livelihoods, where tangible benefits and observable environmental conditions enable closer alignment between perceived importance and valuation (Geijzendorffer & Roche, 2014; Pandeya et al., 2016). Certain regulating services, particularly air quality regulation,

also showed consistent valuation patterns, suggesting clearer links between environmental attributes and perceived benefits.

Cultural services, such as scenic beauty, recreation, and identity, were also well explained by spatial and environmental variables, challenging assumptions that cultural values are purely subjective or weakly linked to biophysical conditions (Alvarez-Codoceo et al., 2021; Thiemann et al., 2022). Across all service categories, spatial proximity, hydrological context, and access to water and sanitation emerged as dominant drivers, as supported by both feature importance and SHAP analyses. These results highlight the central role of accessibility and everyday interaction in shaping ES valuation (Figure 11).

At the same time, several variables exhibited opposing effects across services, revealing trade-offs in social valuation. For example, improved sanitation access increased valuation of recreational services while reducing the perceived importance of irrigation WQ. These contrasting responses illustrate how infrastructural development can reshape priorities rather than uniformly enhancing ES valuation, an insight that is highly relevant for policy design in rapidly urbanising Andean landscapes.

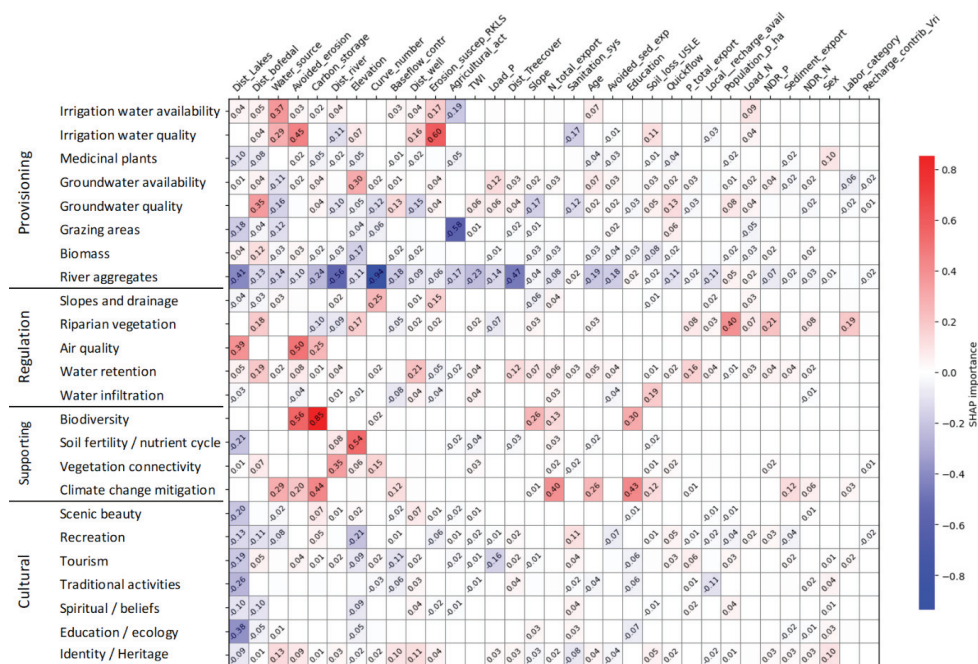


Figure 11. Heatmap of median relative SHAP values illustrating the direction and magnitude of feature contributions across ecosystem service classifications. Variables on the x-axis are ordered by their aggregated mean SHAP contribution across all ecosystem services, while the y-axis shows ecosystem services grouped

by category. Colours represent relative positive and negative influences on model predictions. Figure from Paper IV: (Prado, Rejas, Oporto, Jönsson, Decsi, et al., 2026)

5.4.5 Methodological limitations and uncertainties

Despite integrating extensive survey data and advanced ES modelling, several methodological limitations should be acknowledged. Fieldwork in rural mountain communities was constrained by language and cultural barriers, which may have affected communication, trust, and respondents' understanding of ES concepts, potentially biasing responses toward more tangible provisioning services (Totino et al., 2023). This highlights the limitations of structured surveys in capturing complex socio-cultural values and underscores the need for mixed-method approaches, including participatory and qualitative techniques, to improve contextual understanding and stakeholder engagement (Díaz-Pinzón et al., 2024; Márquez et al., 2023; Tasser et al., 2025).

Uncertainties also arise in the validation of spatially explicit biophysical models, particularly for regulating services. Although model outputs for carbon and nutrient export were compared with WQ measurements at selected catchment outlets, limited data on runoff, sediment transport, and lake level dynamics constrained robust validation. These gaps are critical in mountain systems, where hydrological variability is high, and reliance on statistical comparisons alone may not fully capture spatiotemporal dynamics (Decsi et al., 2022; Díaz-Pinzón et al., 2024). Strengthening field monitoring networks, potentially through community-based initiatives, would improve model validation and increase confidence in ES estimates (Alvarado-Arias et al., 2023; Karimi et al., 2025; McInnes & Everard, 2017).

Overall, integrating local ecological knowledge with enhanced empirical data and participatory valuation methods offers a pathway to better align modelling outputs with community priorities, supporting adaptive and context-sensitive ecosystem management.

5.4.6 Integration with the thesis framework and broader implications

As the final empirical subsection of this thesis, this analysis completes the social-ecological knowledge integration framework by explicitly linking biophysical assessments of WQ and ecosystem functioning with social valuation and governance-relevant outcomes. The alignment between community perceptions and biophysical indicators identified in earlier sections validates the use of RS-derived and modelled variables as meaningful proxies for ES supply. At the same time, the social valuation results reveal dimensions of ES-particularly relational values and perceived deficits-that cannot be inferred from biophysical data alone.

From a theoretical perspective, the findings support the application of complex systems thinking and critical realism by demonstrating that ES values emerge from interactions between material conditions, spatial context, and social structures, rather than from isolated drivers. The use of ML approaches to integrate social, environmental, and spatial data illustrates how methodological innovation can support the co-production of actionable knowledge for water governance.

From a management perspective, the results highlight clear opportunities for participatory water governance, citizen science, and ES-based policy instruments in the study area and similar regions of the Central Andes. High willingness to pay and willingness to participate, combined with strong place-based valuation patterns, suggests that locally tailored, watershed-scale interventions are likely to resonate with community priorities. However, the results also point to limitations, including the cross-sectional nature of perception data and the need for long-term social monitoring to capture dynamic changes in values and expectations.

Overall, this subsection reinforces the central argument of the thesis: that integrated, scalable, and cost-effective freshwater management in data-scarce mountain regions requires the explicit coupling of biophysical monitoring with social perception and valuation. By closing the loop between ecosystem condition, service supply, and societal demand, this final paper strengthens the relevance of the proposed framework and sets the stage for the general conclusions that follow.

6 Conclusions

This thesis develops and applies an integrated social-ecological framework for assessing freshwater ES related to WQ in high-altitude streams and small lakes of the Central Andes. By combining global open-access datasets, RS-derived WQ indicators, ML modelling, targeted field measurements, and socio-economic perceptions, this research advances a cost-effective and scalable approach to ES valuation that can contribute to evidence-based water governance.

Empirical analyses focused on three watersheds characterised by strong physiographic and climatic gradients, increasing LULC pressures, and limited wastewater treatment, conditions that are representative of many headwater systems across the Central Andes. Through a multiscale perspective, the findings provide new insights into how landscape composition, hydrological context, and human activities interact to shape WQ and associated ES.

Importantly, the explicit integration of local perceptions revealed mismatches between ES importance and perceived condition, strengthened the interpretation of biophysical indicators, and highlighted the relevance of both instrumental and relational values for water management. Together, these results demonstrate that linking biophysical assessments with social valuation enhances the identification of conservation priorities, informs ecosystem-based management strategies, and supports the design of participatory and policy-relevant interventions, including willingness to pay for ES and a contribution to integrated watershed governance. The framework developed in this thesis is transferable to other data-scarce mountain regions, offering a robust foundation for sustainable freshwater management under conditions of environmental change.

6.1 Streams and small lakes ecosystem services

The synthesis of lake characteristics across the Andes (Papers I and II) provides the first spatially explicit classification of Andean lakes into eleven lake districts, reflecting coherent patterns in morphology, climate, elevation, and hydrological setting. The analysis confirms that Andean lakes are numerically dominated by small systems ($<10 \text{ km}^2$), while only nine very large lakes account for a substantial proportion of total lake area, particularly in the Central and Southern Andes. The strong spatial autocorrelation of lake attributes supports the relevance of district-

based classification for comparative analysis and ES assessment. This synthesis further identifies pronounced spatial and thematic data gaps, including limited limnological coverage in several Central Andean districts and a near absence of long-term monitoring across most regions. The review of ecological studies identifies multiple interacting threats affecting lake ES, including climate-driven changes in salinity and temperature, eutrophication and browning, biological invasions, enhanced UVR, and expanding mining activities. Together, these findings establish a baseline for understanding lake ES, confirm that Andean lakes are highly vulnerable social-ecological systems, while highlighting structural knowledge gaps that constrain effective management and conservation.

The analysis of LULC influence on stream WQ (Paper III) demonstrates that anthropogenic landscape composition is a dominant control on hydrologic ES in the studied streams, even under hydrologically altered conditions of inter-basin water transfers and dilution effects. These hydro-social interventions partially decouple WQ signals from local LULC pressures, particularly during the dry season, yet strong and consistent relationships remain evident at the catchment scale. Built-up areas, cropland, and managed lawns show the strongest negative associations with WQ parameters and the WQI, while natural land covers contribute buffering effects at riparian and reach scales. The ALCI emerges as a robust integrative proxy for stream WQ in complex, human-modified mountain systems.

The assessment of trophic state and carbon-related dynamics in SHAL (Paper IV) confirms the utility of optical RS indicators for capturing ES-relevant processes in data-scarce Andean environments. Sentinel-2 and Landsat 8&9 corrected reflectance coupled with catchment-scale drivers (e.g. ALCI, *bofedales*) and hydroclimatic variables, showed strong and consistent relationships with Chl-*a*, turbidity, water transparency, and CDOM, enabling spatial differentiation of lake conditions within and across regions. The results demonstrate that small, visually clear high-altitude lakes exhibit substantial variability in productivity and organic matter characteristics, with implications for water supply, carbon regulation, and ecological integrity. These findings validate RS as a scalable tool for lake ES assessment and reinforce its role in complementing field-based monitoring in mountain regions.

The analysis of social perceptions and ES valuation (Paper V) demonstrates that freshwater ES are widely perceived as highly important, yet frequently considered degraded or insufficient, particularly regulating and supporting services. Provisioning services related to water availability and quality showed the strongest alignment between perceived importance and valuation outcomes. XGBoost models successfully identified key socio-environmental drivers of both willingness to pay and willingness to participate, including education level, water access, sanitation infrastructure, proximity to aquatic ecosystems, and catchment condition indicators. Spatial and hydrological variables consistently ranked among the most influential predictors, linking social valuation directly to biophysical context. These results confirm that ES valuation is shaped by both lived experience and environmental

exposure, and that integrating social perceptions with biophysical indicators provides a more complete and actionable representation of freshwater ES in Central Andes regions.

6.2 Integrative framework

This thesis advances freshwater ES by developing and operationalising an integrated analytical framework that combines EO, field data, ML, ES modelling, and socio-cultural valuation within a single social-ecological systems perspective. The primary methodological contribution lies in the structured integration of heterogeneous data sources and analytical approaches into a coherent data-to-valuation workflow, rather than their isolated application. By linking the data flow, the framework enables spatially explicit, cross-scale assessment of freshwater ecosystem condition and services.

Conceptually, the framework is grounded in complex systems thinking and a critical realist understanding of social-ecological systems, recognising water bodies as emergent outcomes of interacting hydrological, ecological, spatial, and social processes. The research advances a Social-Ecological Knowledge Pathway that links system ontology, knowledge co-production, and valuation without collapsing them into a single disciplinary logic. Indicators derived from EO, modelling, and field data are treated as partial and provisional representations of a stratified reality, functioning as boundary objects that connect scientific analysis to governance-relevant understanding rather than as definitive system descriptions.

ES provide the central integrative interface within this framework. By positioning ES as relational outcomes emerging from ecological condition, spatial configuration, and social context, the framework explicitly connects biophysical indicators to socio-cultural values. The incorporation of instrumental, relational, and perceived values alongside biophysical service supply demonstrates how valuation can be analytically integrated rather than appended. Collectively, these methodological and conceptual contributions establish a coherent, systems-oriented framework that enables cross-scale synthesis and transforms diverse datasets into integrated knowledge about freshwater social-ecological systems.

6.3 Policy Implications

The findings of this thesis have direct implications for water resources governance in data-scarce, rapidly transforming mountain regions. By demonstrating how WQ, ES, and social values can be assessed jointly and spatially, the research supports a shift from sectoral and infrastructure-centred water management toward ecosystem-

based and landscape-scale governance. The integrated framework enables water to be positioned as a structuring element of land use planning, highlighting how upstream land use decisions, hydrological alterations, and landscape configuration directly affect downstream WQ, ES provision, and human well-being.

At the operational level, the spatially explicit indicators and ES outputs generated in this thesis can inform land use zoning, watershed prioritisation, and conservation planning, for example by supporting the reinforcement of existing protected areas. The explicit consideration of human water allocations and altered flow regimes provides a basis for incorporating WQ and ES objectives into allocation rules, environmental flow discussions, and watershed-scale planning processes. By linking biophysical assessments with locally grounded socio-cultural values, the framework also supports the design of ecosystem-based management instruments, including recognition of ES value, that are better aligned with stakeholder perceptions and social priorities.

More broadly, the research contributes to international sustainability agendas by providing an applied approach that operationalises key principles of the Sustainable Development Goals, particularly SDG 6 (clean water), SDG 13 (climate action), and SDG 15 (life on land). By integrating EO, modelling, and social valuation within a governance-relevant framework, the thesis supports evidence-based, transparent, and socially legitimate decision-making for sustainable water management in complex social-ecological systems.

6.4 Future Perspectives

The integrated framework developed in this thesis opens several pathways for advancing freshwater ecosystem assessment and governance in mountain regions, while also highlighting priorities for future research and monitoring. One central perspective concerns data continuity and resolution. Although the framework demonstrates that meaningful assessments can be achieved in data-scarce contexts, expanding long-term, harmonised datasets, particularly for WQ key parameters and socio-economic variables, would substantially improve model robustness and temporal sensitivity. Advances in optical RS, data fusion, and cloud-robust approaches will be especially important for improving the characterisation of SHAL, where frequent cloud cover currently constrains observations.

A second avenue for future development lies in broadening the spectrum of pressures and indicators incorporated into the framework. The current analyses do not explicitly address the impacts of extractive and high-pollution activities such as mining, hydrocarbons, and certain industrial sectors, despite their growing relevance in the Andes. Similarly, emerging contaminants, pesticides, and micropollutants remain largely unmonitored in mountain waters, potentially leading to underestimation of risks to ecosystem functioning and human health. Integrating

chemical and biological indicators, including bioindicators of ecological integrity, would allow future applications to better capture cumulative and sub-lethal impacts on freshwater systems.

Finally, future work should explore the scalability and transferability of the framework beyond the studied watersheds. Applying the approach to larger basins, transboundary systems, or socio-ecologically distinct regions will require careful adaptation of model structures, assumptions, and valuation approaches to local governance contexts. At the same time, comparative applications across regions could strengthen the framework's role as a boundary object for cross-scale learning, enabling more coherent integration of scientific evidence into adaptive water governance under accelerating environmental change.

References

- Abdali, E., Valadan Zoej, M. J., Taheri Dehkordi, A., & Ghaderpour, E. (2024). A Parallel-Cascaded Ensemble of Machine Learning Models for Crop Type Classification in Google Earth Engine Using Multi-Temporal Sentinel-1/2 and Landsat-8/9 Remote Sensing Data. *Remote Sensing*, 16(1). <https://doi.org/10.3390/rs16010127>
- Abdelal, Q., Assaf, M. N., Al-Rawabdeh, A., Arabasi, S., & Rawashdeh, N. A. (2022). Assessment of Sentinel-2 and Landsat-8 OLI for Small-Scale Inland Water Quality Modeling and Monitoring Based on Handheld Hyperspectral Ground Truthing. *Journal of Sensors*, 2022. <https://doi.org/10.1155/2022/4643924>
- Abdi, H. (2010). Partial Least Squares Regression and Projection on Latent Structure Regression (PLS Regression). *Wiley Interdisciplinary Reviews: Computational Statistics*, 2(1), 97–106. <https://doi.org/10.1002/wics.51>
- Acosta, F., Aguilera, X., Campero, M., Prado, P., & Fernández, C. E. (2022). Estructura del ensamblaje de microcrustáceos en tres distritos biogeográficos de los Andes de Bolivia. *Ciencia y Tecnología*, 35–45.
- Affinito, F., Holzer, J. M., Fortin, M. J., & Gonzalez, A. (2025). Towards a unified ontology for monitoring ecosystem services. *Ecosystem Services*, 73(February), 101726. <https://doi.org/10.1016/j.ecoser.2025.101726>
- Aguilar, P., Dorador, C., Vila, I., & Sommaruga, R. (2018). Bacterioplankton composition in tropical high-elevation lakes of the Andean plateau. *FEMS Microbiology Ecology*, 94(3), 1–9. <https://doi.org/10.1093/femsec/fiy004>
- Aguilera, X., Lazzaro, X., & Coronel, J. S. (2013). Tropical high-altitude Andean lakes located above the tree line attenuate UV-A radiation more strongly than typical temperate alpine lakes. *Photochemical and Photobiological Sciences*, 12(9), 1649–1657. <https://doi.org/10.1039/c3pp25285j>
- Aguirre, L. F., Burgoa, R. R. D., & Ugón, A. L. A. (2023). *Corredores biológicos urbanos y servicios ecosistémicos en el municipio de Cochabamba, Bolivia*. Universidad Mayor de San Simón.
- Ai, L., Shi, Z. H., Yin, W., & Huang, X. (2015). Spatial and seasonal patterns in stream water contamination across mountainous watersheds: Linkage with landscape characteristics. *Journal of Hydrology*, 523, 398–408. <https://doi.org/10.1016/j.jhydrol.2015.01.082>
- Alamanos, A., Koundouri, P., Papadaki, L., Pliakou, T., & Toli, E. (2022). Water for Tomorrow: A Living Lab on the Creation of the Science-Policy-Stakeholder Interface. *Water (Switzerland)*, 14(18). <https://doi.org/10.3390/w14182879>
- Alcocer, J., Ruiz-Fernández, A. C., Oseguera, L. A., Caballero, M., Sanchez-Cabeza, J. A.,

- Pérez-Bernal, L. H., & Hernández-Rivera, D. M. (2020). Sediment carbon storage increases in tropical, oligotrophic, high mountain lakes. *Anthropocene*, 32. <https://doi.org/10.1016/j.ancene.2020.100272>
- Alexander, R. B., Boyer, E. W., Smith, R. A., Schwarz, G. E., & Moore, R. B. (2007). The role of headwater streams in downstream water quality. *Journal of the American Water Resources Association*, 43(1), 41–59. <https://doi.org/10.1111/j.1752-1688.2007.00005.x>
- Allan, J. D. (2004a). Influence of land use and landscape setting on the ecological status of rivers. *Limnetica*, 23(4), 187–198.
- Allan, J. D. (2004b). Landscapes and riverscapes: The influence of land use on stream ecosystems. In *Annual Review of Ecology, Evolution, and Systematics* (Vol. 35, pp. 257–284). <https://doi.org/10.1146/annurev.ecolsys.35.120202.110122>
- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements* (Vol. 56). Food and Agriculture Organization of the United Nations.
- Almeida, I., Rösch, C., & Saha, S. (2018). Comparison of ecosystem services from mixed and monospecific forests in Southwest Germany: A survey on public perception. *Forests*, 9(10). <https://doi.org/10.3390/f9100627>
- Alvarado-Arias, N., Moya-Almeida, V., Cabrera-Torres, F., & Medina-Enríquez, A. (2023). Evaluation and mapping of the positive and negative social values for the urban river ecosystem. *One Ecosystem*, 8. <https://doi.org/10.3897/oneeco.8.e101122>
- Alvarez-Codoceo, S., Cerda, C., & Perez-Quezada, J. F. (2021). Mapping the provision of cultural ecosystem services in large cities: The case of The Andean piedmont in Santiago, Chile. *Urban Forestry and Urban Greening*, 66, 127390. <https://doi.org/10.1016/j.ufug.2021.127390>
- Ambrose-Igho, G., Seyoum, W. M., Perry, W. L., & O'Reilly, C. M. (2021). Spatiotemporal Analysis of Water Quality Indicators in Small Lakes Using Sentinel-2 Satellite Data: Lake Bloomington and Evergreen Lake, Central Illinois, USA. *Environmental Processes*, 8(2), 637–660. <https://doi.org/10.1007/s40710-021-00519-x>
- Anselin, L. (1995). Local Indicators of Spatial Association—LISA. *Geographical Analysis*, 27(2), 93–115. <https://doi.org/10.1111/j.1538-4632.1995.tb00338.x>
- Archer, M., Bhaskar, R., Collier, A., Lawson, T., & Norrie, A. (Eds.). (1998). *Critical Realism: Essential Readings*. Routledge.
- Arias-Rodriguez, L. F., Duan, Z., Díaz-Torres, J. de J., Basilio Hazas, M., Huang, J., Kumar, B. U., Tuo, Y., & Disse, M. (2021). Integration of remote sensing and Mexican water quality monitoring system using an extreme learning machine. *Sensors*, 21(12). <https://doi.org/10.3390/s21124118>
- Arismendi, I., Penaluna, B. E., Gomez-Uchida, D., Di Prinzio, C., Rodríguez-Olarte, D., Carvajal-Vallejos, F. M., Mojica, J. I., Mazzoni, R., Cussac, V., Maldonado, M., Pellegrini Caramaschi, E., Zeballos, A. J., Villalba, A., Van Damme, P. A., Córdova, L., Iglesias-Ríos, R., Cañas-Rojas, D., Cañas-Merino, M., Benavente, J. N., ... Savaria, P. (2019). Trout and Char of South America. In J. L. Kershner, J. E. Williams, R. E. Gresswell, & J. Lobón-Cerviá (Eds.), *Trout and Char of the World* (pp. 279–311). American Fisheries Society. <https://doi.org/10.47886/9781934874547.ch9>

- Arrow, K. J., Dasgupta, P., Goulder, L. H., Mumford, K. J., & Oleson, K. (2012). Sustainability and the measurement of wealth. *Environment and Development Economics*, 17(3), 317–353. <https://doi.org/10.1017/S1355770X12000137>
- Asmare, B., Neculina, A., Wubie, A., Egbe, A. M., Charleine, D. S., & Ambo, F. B. (2024). The impact of land use and land cover change on the stream water quality in Limbe I municipality, Cameroon. *Environmental Quality Management*, 34(2). <https://doi.org/10.1002/tqem.22254>
- Baatrup-Pedersen, A., Larsen, S. E., Andersen, D. K., Jepsen, N., Nielsen, J., & Rasmussen, J. J. (2018). Headwater streams in the EU Water Framework Directive: Evidence-based decision support to select streams for river basin management plans. *Science of the Total Environment*, 613–614, 1048–1054. <https://doi.org/10.1016/j.scitotenv.2017.09.199>
- Baek, S. S., Pyo, J., & Chun, J. A. (2020). Prediction of water level and water quality using a cnn-lstm combined deep learning approach. *Water (Switzerland)*, 12(12). <https://doi.org/10.3390/w12123399>
- Bai, Y., Huang, Q., Inostroza, L., Xu, H., Yin, D., Liu, Z., Zhang, L., & Xu, F. (2024). Residents' perceptions of ecosystem services in an urbanizing basin: A case study in the Guanting Reservoir basin, China. *Geography and Sustainability*, 5(3), 430–444. <https://doi.org/10.1016/j.geosus.2024.04.004>
- Baltodano, A., Agramont, A., Reusen, I., & van Griensven, A. (2022). Land Cover Change and Water Quality: How Remote Sensing Can Help Understand Driver–Impact Relations in the Lake Titicaca Basin. *Water (Switzerland)*, 14(7). <https://doi.org/10.3390/w14071021>
- Balvanera, P., Pfisterer, A. B., Buchmann, N., He, J. S., Nakashizuka, T., Raffaelli, D., & Schmid, B. (2006). Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecology Letters*, 9(10), 1146–1156. <https://doi.org/10.1111/j.1461-0248.2006.00963.x>
- Balvanera, P., Uriarte, M., Almeida-Leñero, L., Altesor, A., DeClerck, F., Gardner, T., Hall, J., Lara, A., Lateral, P., Peña-Claros, M., Silva Matos, D. M., Vogl, A. L., Romero-Duque, L. P., Arreola, L. F., Caro-Borrero, Á. P., Gallego, F., Jain, M., Little, C., de Oliveira Xavier, R., ... Vallejos, M. (2012). Ecosystem services research in Latin America: The state of the art. *Ecosystem Services*, 2, 56–70. <https://doi.org/10.1016/j.ecoser.2012.09.006>
- Bassa, Z. (2024). Empirical Review on Determinants of Willingness to Pay for Natural and Environmental Resource Valuation: Meta-Analysis . *International Journal of Economy, Energy and Environment*, 9(3), 77–89. <https://doi.org/10.11648/j.ijeee.20240903.12>
- Batina, A., & Krtalić, A. (2024). Integrating Remote Sensing Methods for Monitoring Lake Water Quality: A Comprehensive Review. *Hydrology*, 11(7). <https://doi.org/10.3390/hydrology11070092>
- Battin, T. J., Louis A. Kaplan, Stuart Findlay, Charles S. Hopkinson, Eugenia Marti, Aaron I. Packman, J. Denis Newbold, & Francesc Sabater. (2008). Biophysical controls on organic carbon fluxes in fluvial networks. *Nature Geoscience*, 1(2), 95–100.
- Beck, R., Zhan, S., Liu, H., Tong, S., Yang, B., Xu, M., Ye, Z., Huang, Y., Shu, S., Wu, Q.,

- Wang, S., Berling, K., Murray, A., Emery, E., Reif, M., Harwood, J., Young, J., Nietch, C., Macke, D., ... Su, H. (2016). Comparison of satellite reflectance algorithms for estimating chlorophyll-a in a temperate reservoir using coincident hyperspectral aircraft imagery and dense coincident surface observations. *Remote Sensing of Environment*, 178, 15–30. <https://doi.org/10.1016/j.rse.2016.03.002>
- Beek, K. J., & Wright, A. C. S. (1971). *Estudios regionales sobre recursos de suelos: mapas de suelos de América Latina preparados para FAO/UNESCO* (Rome: FAO/). FAO/UNESCO.
- Belgiu, M., & Drăgu, L. (2016). Random forest in remote sensing: A review of applications and future directions. *ISPRS Journal of Photogrammetry and Remote Sensing*, 114, 24–31. <https://doi.org/10.1016/j.isprsjprs.2016.01.011>
- Belton, V., & Stewart, T. J. (2002). *Multiple Criteria Decision Analysis: An Integrated Approach*. Springer. <https://doi.org/10.1007/978-1-4615-1495-4>
- Berkes, F., Colding, J., & Folke, C. (Eds.). (2003). *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. Cambridge University Press.
- Bettencourt, L. M. A., & Kaur, J. (2011). Evolution and structure of sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, 108(49), 19540–19545. <https://doi.org/10.1073/pnas.1102712108>
- Bhaskar, R. (1975). *A Realist Theory of Science*. Leeds Books.
- Bhaskar, R. (1979). *The Possibility of Naturalism: A Philosophical Critique of the Contemporary Human Sciences*. Brighton Harvester.
- Bhattarai, R., & Dutta, D. (2006). Estimation of Soil Erosion and Sediment Yield Using GIS at Catchment Scale. *Water Resources Management*, 21, 1635–1647. <https://doi.org/10.1007/s11269-006-9118-8>
- Bieroza, M., Hallberg, L., Livsey, J., Prischl, L. A., & Wynants, M. (2024). Recognizing Agricultural Headwaters as Critical Ecosystems. *Environmental Science and Technology*, 58(11), 4852–4858. <https://doi.org/10.1021/acs.est.3c10165>
- Blix, K., Pálffy, K., Tóth, V. R., & Eltoft, T. (2018). Remote sensing of water quality parameters over Lake Balaton by using Sentinel-3 OLCI. *Water (Switzerland)*, 10(10), 1–20. <https://doi.org/10.3390/w10101428>
- Blöschl, G. (2013). *Runoff prediction in ungauged basins: synthesis across processes, places and scales*. Cambridge University Press.
- Blöschl, G., Bierkens, M. F. P., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., Kirchner, J. W., McDonnell, J. J., Savenije, H. H. G., Sivapalan, M., Stumpp, C., Toth, E., Volpi, E., Carr, G., Lupton, C., Salinas, J., Széles, B., Viglione, A., Aksoy, H., ... Zhang, Y. (2019). Twenty-three unsolved problems in hydrology (UPH)—a community perspective. *Hydrological Sciences Journal*, 64(10), 1141–1158. <https://doi.org/10.1080/02626667.2019.1620507>
- Boampong, M. S., Boakye-Danquah, J., Boafo, Y. A., Appiagyei, K., Tweneboah-Koduah, D., & Antwi, E. K. (2024). Experiences of inequality in international collaborative research – Perspectives from environmental and sustainability scholars from Ghana, West Africa. *Environmental Science and Policy*, 152(May 2023), 103661. <https://doi.org/10.1016/j.envsci.2023.103661>
- Ley N°1333 del Medio Ambiente: Reglamento en Materia de Contaminación Hídrica

- (RMCH), (1992). <https://www.mmaya.gob.bo/>
- Bonnedahl, K. J., Heikkurinen, P., & Paavola, J. (2022). Strongly sustainable development goals: Overcoming distances constraining responsible action. *Environmental Science and Policy*, 129(January), 150–158. <https://doi.org/10.1016/j.envsci.2022.01.004>
- Borselli, L., Cassi, P., & Torri, D. (2008). Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. *Catena*, 75(3), 268–277. <https://doi.org/10.1016/j.catena.2008.07.006>
- Boyle, E. S., Guerriero, N., Thiallet, A., Del Vecchio, R., & Blough, N. V. (2009). Optical properties of humic substances and CDOM: Relation to structure (Environmental Science and Technology (2009) 43, (2262-2268)). *Environmental Science and Technology*, 43(12), 4612. <https://doi.org/10.1021/es901255m>
- Braat, L. C., & de Groot, R. (2012). The ecosystem services agenda: bridging the worlds of natural science and economics, conservation and development, and public and private policy. *Ecosystem Services*, 1(1), 4–15. <https://doi.org/10.1016/j.ecoser.2012.07.011>
- Brain, K. A. (2017). The impacts of mining on livelihoods in the Andes: A critical overview. *Extractive Industries and Society*, 4(2), 410–418. <https://doi.org/10.1016/j.exis.2017.03.001>
- Brander, L. M., de Groot, R., Schägner, J. P., Guisado-Goñi, V., van 't Hoff, V., Solomonides, S., McVittie, A., Eppink, F., Sposato, M., Do, L., Ghermandi, A., Sinclair, M., & Thomas, R. (2024). Economic values for ecosystem services: A global synthesis and way forward. *Ecosystem Services*, 66(August 2023). <https://doi.org/10.1016/j.ecoser.2024.101606>
- Breiman, L. (2001). Random forests. *Machine Learning*, 45(1), 5–32. <https://doi.org/10.1023/A:1010933404324>
- Breusch, A. T. S., & Pagan, A. R. (2008). *A Simple Test for Heteroscedasticity and Random Coefficient Variation Published by: The Econometric Society Stable URL: http://www.jstor.org/stable/1911963*. 47(5), 1287–1294.
- Brezonik, P., Menken, K. D., & Bauer, M. (2005). Landsat-based remote sensing of lake water quality characteristics, including chlorophyll and colored dissolved organic matter (CDOM). *Lake and Reservoir Management*, 21(4), 373–382. <https://doi.org/10.1080/07438140509354442>
- Brockmann, C., Doerffer, R., Peters, M., Stelzer, K., Embacher, S., & Ruescas, A. (2016). Evolution of the C2rcc Neural Network for Sentinel 2 and 3 for the Retrieval of Ocean Colour Products in Normal and Extreme Optically Complex Waters. *Living Planet Symposium 2016*, 9–13.
- Brönmark, C., & Hansson, L. A. (2017). The biology of lakes and ponds. In *The Biology of Lakes and Ponds* (3rd ed.). Oxford University Press. <https://doi.org/10.1093/oso/9780198713593.001.0001>
- Brown, P. D., Wurtsbaugh, W. A., & Nydick, K. R. (2008). Lakes and forests as determinants of downstream nutrient concentrations in small mountain watersheds. *Arctic, Antarctic, and Alpine Research*, 40(3), 462–469. [https://doi.org/10.1657/1523-0430\(07-052\)\[BROWN\]2.0.CO;2](https://doi.org/10.1657/1523-0430(07-052)[BROWN]2.0.CO;2)
- Brown, R. M., L. McClelland, N., Deiningner, R. A., & Tozer, R. G. (1970). A water quality index - do we dare?*. *Water and Sewage Works*, 117(10).

- Brutsaert, W. (2023). *Hydrology: an introduction*. Cambridge University Press.
- Bu, H., Meng, W., Zhang, Y., & Wan, J. (2014). Relationships between land use patterns and water quality in the Taizi River basin, China. *Ecological Indicators*, 41, 187–197. <https://doi.org/10.1016/j.ecolind.2014.02.003>
- Caballero, I., & Stumpf, R. P. (2020). Atmospheric correction for satellite-derived bathymetry in the Caribbean waters: from a single image to multi-temporal approaches using Sentinel-2A/B. *Optics Express*, 28(8), 11742. <https://doi.org/10.1364/oe.390316>
- California Regional Water Quality Control Board, Central Coast Region. (2013). *Total Maximum Daily Loads for Nitrogen Compounds and Orthophosphate for the Lower Salinas River and Reclamation Canal Basin, and the Moro Cojo Slough Subwatershed, Monterey County, CA. Appendix F*. https://www.waterboards.ca.gov/centralcoast/water_issues/programs/tmdl/docs/salinas/nutrients/index.html
- Campero, M., Balseiro, E., Fernández, C. E., Modenutti, B., Prado, P. E., Rivera-Rondon, C. A., Carvajal-Vallejos, F. M., Herrera-Martínez, Y., López-Paría, D. M., Aranguren-Riaño, N., Samanez, I., De los Ríos-Escalante, P. R., & Steinitz-Kannan, M. (2024). Andean lakes: endangered by natural and anthropogenic threats. *Inland Waters*, 14(4), 352–368. <https://doi.org/10.1080/20442041.2024.2395157>
- Canedoli, C., Rota, N., Vogiatzakis, I. N., Zanchi, A., Drius, M., Nagendra, H., & Padoa-Schioppa, E. (2024). Review of indicators for mountain ecosystem services: Are the most frequently used also the best? *Ecological Indicators*, 166(February), 112310. <https://doi.org/10.1016/j.ecolind.2024.112310>
- Capolupo, A., Monterisi, C., Saponaro, M., & Tarantino, E. (2020). *Multi-temporal analysis of land cover changes using Landsat data through Google Earth Engine platform*. 69. <https://doi.org/10.1117/12.2571228>
- Carlson, R. E. (1977). A trophic state index for lakes. *Limnology and Oceanography*, 22(2), 361–369. <https://doi.org/10.4319/lo.1977.22.2.0361>
- Carpenter, S. R., Cole, J. J., Pace, M. L., Batt, R., Brock, W. A., Cline, T., Coloso, J., Hodgson, J. R., Kitchell, J. F., Seekell, D. A., & others. (2011). Early warnings of regime shifts: a whole-ecosystem experiment. *Science*, 332(6033), 1079–1082.
- Casey, K. A., Rousseaux, C. S., Gregg, W. W., Boss, E., Chase, A. P., Craig, S. E., Mouw, C. B., Reynolds, R. A., Stramski, D., Ackleson, S. G., Bricaud, A., Schaeffer, B., Lewis, M. R., & Maritorena, S. (2020). A global compilation of in situ aquatic high spectral resolution inherent and apparent optical property data for remote sensing applications. *Earth System Science Data*, 12(2), 1123–1139. <https://doi.org/10.5194/essd-12-1123-2020>
- Castro-Díaz, R., Delgado, L. E., Langle-Flores, A., Perevochtchikova, M., & Marín, V. H. (2022). A systematic review of social participation in ecosystem services studies in Latin America from a transdisciplinary perspective, 1996–2020. *Science of the Total Environment*, 828, 154523. <https://doi.org/10.1016/j.scitotenv.2022.154523>
- Castro, C. C., Gómez, J. A. D., Martín, J. D., Sánchez, B. A. H., Arango, J. L. C., Tuya, F. A. C., & Díaz-Varela, R. (2020). An UAV and satellite multispectral data approach to monitor water quality in small reservoirs. *Remote Sensing*, 12(9). <https://doi.org/10.3390/RS12091514>

- Cauvy-Fraunié, S., & Dangles, O. (2019). A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology and Evolution*, 3(12), 1675–1685. <https://doi.org/10.1038/s41559-019-1042-8>
- Center for International Earth Science Information Network - CIESIN - Columbia University. (2018). *Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11*. NASA Socioeconomic Data and Applications Center (SEDAC). <https://doi.org/10.7927/H49C6VHW>
- Cerretelli, S., Poggio, L., Gimona, A., Yakob, G., Boke, S., Habte, M., Coull, M., Peressotti, A., & Black, H. (2018). Spatial assessment of land degradation through key ecosystem services: The role of globally available data. *Science of the Total Environment*, 628–629, 539–555. <https://doi.org/10.1016/j.scitotenv.2018.02.085>
- Chanamé-Zapata, F., Custodio, M., Poma-Chávez, C., & Huamán-De La Cruz, A. (2020). Nutrient concentrations and trophic state of three Andean lakes from Junín, Perú. *Revista Ambiente e Agua*. <https://doi.org/doi:10.4136/ambi-agua.2525>
- Chatzinikolaou, P., Viaggi, D., & Raggi, M. (2018). *Review of Multicriteria Methodologies and Tools for the Evaluation of the Provision of Ecosystem Services*. 43–68. https://doi.org/10.1007/978-3-319-76929-5_2
- Chaudhry, M., Shafi, I., Mahnoor, M., Vargas, D. L. R., Thompson, E. B., & Ashraf, I. (2023). A Systematic Literature Review on Identifying Patterns Using Unsupervised Clustering Algorithms: A Data Mining Perspective. *Symmetry*, 15(9), 1–44. <https://doi.org/10.3390/sym15091679>
- Chaves-Chaparro, J., Aguirre-Bastos, C., & Domínguez-Gómez, J. A. (2025). The sustainability science approach in sub-Saharan Africa: key lessons from five case studies. *Sustainability Science*, 20(3), 677–689. <https://doi.org/10.1007/s11625-024-01616-0>
- Chen, J., Zhu, W., Tian, Y. Q., Yu, Q., Zheng, Y., & Huang, L. (2017). Remote estimation of colored dissolved organic matter and chlorophyll-a in Lake Huron using Sentinel-2 measurements. *Journal of Applied Remote Sensing*, 11(03), 1. <https://doi.org/10.1117/1.jrs.11.036007>
- Chen, L., Fu, B., & Zhao, W. (2008). Source-sink landscape theory and its ecological significance. *Frontiers of Biology in China*, 3(2), 131–136. <https://doi.org/10.1007/s11515-008-0026-x>
- Chen, T., & Guestrin, C. (2016). XGBoost: A scalable tree boosting system. *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, 785–794. <https://doi.org/10.1145/2939672.2939785>
- Cheng, C., Wei, Y., Lv, G., & Yuan, Z. (2013). Remote estimation of chlorophyll-a concentration in turbid water using a spectral index: a case study in Taihu Lake, China. *Journal of Applied Remote Sensing*, 7(1), 073465. <https://doi.org/10.1117/1.jrs.7.073465>
- Clark, W. C. (2007). Sustainability science: A room of its own. *Proceedings of the National Academy of Sciences of the United States of America*, 104(6), 1737–1738. <https://doi.org/10.1073/pnas.0611291104>
- Clark, W. C., & Harley, A. G. (2020). Sustainability science: Toward a synthesis. *Annual Review of Environment and Resources*, 45, 331–386. <https://doi.org/10.1146/annurev->

- Cohen, J. (1960). A Coefficient of Agreement for Nominal Scales. *Educational and Psychological Measurement*, 20(1), 37–46. <https://doi.org/10.1177/001316446002000104>
- Cole, H. S. D., Freeman, C., Jahoda, M., & Pavitt, K. (1973). *Models of Doom: A Critique of the Limits to Growth*. Universe Books.
- Congalton, R. G. (1988). A comparison of sampling schemes used in generating error matrices for assessing the accuracy of maps generated from remotely sensed data. *Photogrammetric Engineering & Remote Sensing*, 54(5), 593–600.
- Contraloría General del Estado Plurinacional de Bolivia (CGE). (2020). *Informe de supervisión K2/GP22/S20-G1: Supervisión a la gestión ambiental sobre la contaminación en el río Chijllawiri*. <https://www.contraloria.gob.bo/>
- Cord, A. F., Brauman, K. A., Chaplin-Kramer, R., Huth, A., Ziv, G., & Seppelt, R. (2017). Priorities to Advance Monitoring of Ecosystem Services Using Earth Observation. *Trends in Ecology and Evolution*, 32(6), 416–428. <https://doi.org/10.1016/j.tree.2017.03.003>
- Costanza, R. (2020). Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. *Ecosystem Services*, 43, 101096. <https://doi.org/https://doi.org/10.1016/j.ecoser.2020.101096>
- Costanza, R., D’Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., & Van Den Belt, M. (1997). The value of the world’s ecosystem services and natural capital. *Nature*, 387(6630), 253–260. <https://doi.org/10.1038/387253a0>
- Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., & Grasso, M. (2017). Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosystem Services*, 28, 1–16. <https://doi.org/10.1016/j.ecoser.2017.09.008>
- Cui, D., Liang, S., Wang, D., & Liu, Z. (2021). *A 1 km global dataset of historical (1979 – 2013) and future (2020 – 2100) Köppen – Geiger climate classification and bioclimatic variables*. 5087–5114.
- Custodio, M., Álvarez, D., Cuadrado, W., Montalvo, R., & Ochoa, S. (2020). Potentially toxic metals and metalloids in surface water intended for human consumption and other uses in the Mantaro River watershed, Peru. *Soil and Water Research*, 15(4), 237–245. <https://doi.org/10.17221/152/2019-SWR>
- Custodio, M., Chirinos, C., & Peñaloza, R. (2020). Behavior of physicochemical parameters and potentially toxic metals in surface water evaluated by means of multimetric indices: A case study in a protected natural area of Peru. *Polish Journal of Environmental Studies*, 29(3), 2111–2123. <https://doi.org/10.15244/pjoes/110933>
- Custodio, M., Cuadrado, W., Peñaloza, R., Montalvo, R., Ochoa, S., & Quispe, J. (2020). Human risk from exposure to heavy metals and arsenic in water from rivers with mining influence in the Central Andes of Peru. *Water (Switzerland)*, 12(7). <https://doi.org/10.3390/w12071946>
- Cutler, D. R., Edwards, T. C., Beard, K. H., Cutler, A., Hess, K. T., Gibson, J., & Lawler, J. J. (2007). Random Forests for Classification in Ecology. *Ecology*, 88(11), 2783–2792.

- <https://doi.org/10.1890/07-0539.1>
- Daily, G. (1997). Introduction. What are Ecosystem Services? In G. Daily (Ed.), *Nature's Services: Societal Dependence on Natural Ecosystems* (Issue January, pp. 1–10). Island Press.
- Daily, G. C. (Ed.). (1997). *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press.
- Daily, G. C., Polasky, S., Goldstein, J., Kareiva, P. M., Mooney, H. A., Pejchar, L., Ricketts, T. H., Salzman, J., & Shallenberger, R. (2009). Ecosystem services in decision making: time to deliver. *Frontiers in Ecology and the Environment*, 7(1), 21–28. <https://doi.org/10.1890/080025>
- Daly, H. E. (1977). *Steady-State Economics*. W.H. Freeman.
- Daly, H. E., & Cobb, J. B. (1989). *For the Common Good: Redirecting the Economy toward Community, the Environment, and a Sustainable Future*. Beacon Press.
- Das, S., Jain, M. K., Gupta, V., McGehee, R. P., Yin, S., de Mello, C., Borrelli, P., & Panagos, P. (2024). GloRESatE: A dataset for global rainfall erosivity derived from multi-source data. *Scientific Data*, 11(1), 926. <https://doi.org/10.1038/s41597-024-03756-5>
- De Groot, R. S. (1987). Environmental Functions as a Unifying Concept for Ecology and Economics. *The Environmentalist*, 7(2), 105–109. <https://doi.org/10.1007/BF02240292>
- De Keukelaere, L., Sterckx, S., Adriaensen, S., Knaeps, E., Reusen, I., Giardino, C., Bresciani, M., Hunter, P., Neil, C., Van der Zande, D., & Vaiciute, D. (2018). Atmospheric correction of Landsat-8/OLI and Sentinel-2/MSI data using iCOR algorithm: validation for coastal and inland waters. *European Journal of Remote Sensing*, 51(1), 525–542. <https://doi.org/10.1080/22797254.2018.1457937>
- Decsi, B., Ács, T., Jolánkai, Z., Kardos, M. K., Koncsos, L., Vári, Á., & Kozma, Z. (2022). From simple to complex – Comparing four modelling tools for quantifying hydrologic ecosystem services. *Ecological Indicators*, 141(August). <https://doi.org/10.1016/j.ecolind.2022.109143>
- Dias, R. C., Seixas, P. C., & Lobner, N. (2020). Sustainable Development and Ecological Modernization: Boundary Discourses between “Strong” and “Weak” Approaches. *Journal of Sustainable Development*, 13(4), 268. <https://doi.org/10.5539/jsd.v13n4p268>
- Díaz-Pinzón, L., Sierra, L., Trillas, F., & Verd, J. M. (2024). The Social-Ecological System Framework of Urban Wetlands: The Role of Collective Management at Local Level. *International Journal of the Commons*, 18(1), 649–669. <https://doi.org/10.5334/ijc.1399>
- Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I. A., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P. W., van Oudenhoven, A. P. E., van der Plaats, F., Schröter, M., Lavorel, S., ... Shirayama, Y. (2018). Assessing nature's contributions to people. *Science*, 359(6373), 270–272. <https://doi.org/10.1126/science.aap8826>
- Dietz, S., & Neumayer, E. (2007). Weak and strong sustainability in the SEEA: Concepts and measurement. *Ecological Economics*, 61(4), 617–626.

- <https://doi.org/10.1016/j.ecolecon.2006.09.007>
- Duque, J., Anselin, L., & Rey, S. (2012). the Max-P-Regions Problem*. *Journal of Regional Science*. <http://onlinelibrary.wiley.com/doi/10.1111/j.1467-9787.2011.00743.x/full>
- Durbin, J., & Watson, G. S. (1951). Testing for serial correlation in least squares regression. II. *Biometrika*, 38(1–2), 159–178. <https://doi.org/10.1093/biomet/38.1-2.159>
- Ebner, M., Fontana, V., Schirpke, U., & Tappeiner, U. (2022). Stakeholder perspectives on ecosystem services of mountain lakes in the European Alps. *Ecosystem Services*, 53(May 2021), 101386. <https://doi.org/10.1016/j.ecoser.2021.101386>
- Ehrlich, P. R. (1971). *Population, Resources, Environment: Issues in Human Ecology*. W.H. Freeman.
- Ehrlich, P. R., & Ehrlich, A. H. (1981). *Extinction: The Causes and Consequences of the Disappearance of Species*. Random House.
- Ehrlich, P. R., Ehrlich, A. H., & Holdren, J. P. (1977). *Ecoscience: Population, Resources, Environment*. W.H. Freeman.
- Ehrlich, P. R., & Mooney, H. A. (1983). Extinction, Substitution, and Ecosystem Services. *BioScience*, 33(4), 248–254. <https://doi.org/10.2307/1309037>
- Ekins, P., Simon, S., Deutsch, L., Folke, C., & De Groot, R. (2003). A framework for the practical application of the concepts of critical natural capital and strong sustainability. *Ecological Economics*, 44(2–3), 165–185. [https://doi.org/10.1016/S0921-8009\(02\)00272-0](https://doi.org/10.1016/S0921-8009(02)00272-0)
- Empresa Nacional de Electricidad CORANI (ENDE). (2023). *Memoria Anual 2023*. <https://www.endecorani.bo/>
- Endreny, T. A., & Wood, E. F. (2003). Watershed weighting of export coefficients to map critical phosphorus loading areas. *Journal of the American Water Resources Association*, 39(1), 165–181.
- Espinoza, J. C., Garreaud, R., Poveda, G., Arias, P. A., Molina-Carpio, J., Masiokas, M., Viale, M., & Scaff, L. (2020). Hydroclimate of the Andes Part I: Main Climatic Features. *Frontiers in Earth Science*, 8(March), 1–20. <https://doi.org/10.3389/feart.2020.00064>
- Esri. (2023). *Grouping Analysis (Spatial Statistics) — ArcGIS Pro Tool Reference*. Environmental Systems Research Institute.
- Evans, C. D., Freeman, C., Monteith, D. T., Reynolds, B., & Fenner, N. (2002). Climate change (Communication arising): Terrestrial export of organic carbon. *Nature*, 415(6874), 862. <https://doi.org/10.1038/415862a>
- Falkenmark, M., & Folke, C. (2002). The ethics of socio-ecohydrological catchment management: Towards hydrosolidarity. *Hydrology and Earth System Sciences*, 6(1), 1–9. <https://doi.org/10.5194/hess-6-1-2002>
- Falkenmark, M., & Rockström, J. (2006). The new blue and green water paradigm: Breaking new ground for water resources planning. *Journal of Water Resources Planning and Management*, 132(3), 129–132. [https://doi.org/10.1061/\(ASCE\)0733-9496\(2006\)132:3\(129\)](https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129))
- Fan, Y., Chen, J., Shirkey, G., John, R., Wu, S. R., Park, H., & Shao, C. (2016). Applications of structural equation modeling (SEM) in ecological studies: an updated review.

- Ecological Processes*, 5(1). <https://doi.org/10.1186/s13717-016-0063-3>
- Fernández, C. E., Campero, M., Acosta, F., Prado, P. E., Maldonado, M., Goitia, E., Stamou, G., Michaloudi, E., & López, C. (2024). Diversity of Rotifera in Freshwaters of Bolivia: An Updated Checklist. *Diversity*, 16(9), 1–8. <https://doi.org/10.3390/d16090589>
- Fernández, C. E., & Rejas, D. (2017). Effects of UVB radiation on grazing of two cladocerans from high-altitude Andean lakes. *PLoS ONE*, 12(4). <https://doi.org/10.1371/journal.pone.0174334>
- Fichot, C. G., & Benner, R. (2011). A novel method to estimate DOC concentrations from CDOM absorption coefficients in coastal waters. *Geophysical Research Letters*, 38(3), 1–5. <https://doi.org/10.1029/2010GL046152>
- Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: new 1 km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12), 4302–4315. <https://doi.org/10.1002/joc.5086>
- Folke, C., Biggs, R., Norström, A. V., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society*, 21(3). <https://doi.org/10.5751/ES-08748-210341>
- Food and Agriculture Organization of the United Nations. (2006). *Guidelines for Soil Description* (4th ed.). FAO.
- Freeman, C., Evans, C. D., Monteith, D. T., Reynolds, B., & Fenner, N. (2001). Export of organic carbon from peat soils. *Nature*, 412(6849), 785. <https://doi.org/10.1038/35090628>
- Fuentes-Rivas, R. M., Ramos-Leal, J. A., Jiménez-Moleón, M. del C., & Esparza-Soto, M. (2015). Caracterización de la Materia Orgánica Disuelta en Agua Subterránea del Valle de Toluca Mediante Espectrofotometría de fluorescencia 3D. *Revista Internacional de Contaminación Ambiental*, 31(3), 253–264.
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. *Scientific Data*, 2, 1–21. <https://doi.org/10.1038/sdata.2015.66>
- Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. *Futures*, 25(7), 739–755. [https://doi.org/10.1016/0016-3287\(93\)90022-L](https://doi.org/10.1016/0016-3287(93)90022-L)
- Funtowicz, S., & Ravetz, J. (2025). Knowledge, power, and participation in the post-normal age. *Ecological Economics*, 237(June), 108716. <https://doi.org/10.1016/j.ecolecon.2025.108716>
- Fustos-Toribio, I., Basualto, D., Gatica, A., Bravo-Alarcón, A., Palma, J. L., Fuentealba, G., & Sepúlveda, S. A. (2025). Controls over debris flow initiation in glacio-volcanic environments in the Southern Andes. *Natural Hazards and Earth System Sciences*, 25(12), 4843–4861. <https://doi.org/10.5194/nhess-25-4843-2025>
- Gao, B.-C. (1996). NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, 58(3), 257–266. [https://doi.org/10.1016/S0034-4257\(96\)00067-3](https://doi.org/10.1016/S0034-4257(96)00067-3)
- Gao, H., Sabo, J. L., Chen, X., Liu, Z., Yang, Z., Ren, Z., & Liu, M. (2018). Landscape heterogeneity and hydrological processes: a review of landscape-based hydrological

- models. In *Landscape Ecology* (Vol. 33, Issue 9, pp. 1461–1480). Springer Netherlands. <https://doi.org/10.1007/s10980-018-0690-4>
- Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., & Veloso-Aguila, D. (2019). The Central Chile Mega Drought (2010–2018): A climate dynamics perspective. *International Journal of Climatology*. <https://doi.org/10.1002/joc.6219>
- Gazzaz, N. M., Yusoff, M. K., Aris, A. Z., Juahir, H., & Ramli, M. F. (2012). Artificial neural network modeling of the water quality index for Kinta River (Malaysia) using water quality variables as predictors. *Marine Pollution Bulletin*, 64(11), 2409–2420. <https://doi.org/10.1016/j.marpolbul.2012.08.005>
- Geijzendorffer, I. R., & Roche, P. K. (2014). The relevant scales of ecosystem services demand. *Ecosystem Services*, 10, 49–51. <https://doi.org/https://doi.org/10.1016/j.ecoser.2014.09.002>
- Georgescu-Roegen, N. (1975). Energy and Economic Myths. *Southern Economic Journal*, 41(3), 347–381. <https://doi.org/10.2307/1056148>
- Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A comprehensive review on water quality parameters estimation using remote sensing techniques. *Sensors (Switzerland)*, 16(8). <https://doi.org/10.3390/s16081298>
- Giri, C., & Long, J. (2014). Land cover characterization and mapping of South America for the year 2010 using landsat 30 m satellite data. *Remote Sensing*, 6(10), 9494–9510. <https://doi.org/10.3390/rs6109494>
- Gobierno Autónomo Departamental de Cochabamba (GADC). (2019). *Plan Director de la Cuenca del Río Rocha*. <https://www.sei.org/wp-content/uploads/2020/02/resumen-ejecutivo-rio-rocha.pdf>
- Gobierno Autónomo Municipal de Quillacollo (GAMQ). (2021). *Plan Territorial de Desarrollo Integral del Municipio de Quillacollo 2021-2025*. <https://www.quillacollo.gob.bo/images/ptdi/PTDI FINAL 2021-2025.pdf>
- Gordon, N. D., McMahon, T. A., & Finlayson, B. L. (2004). Stream hydrology: an introduction for ecologists. In *Stream hydrology: an introduction for ecologists*. [https://doi.org/10.1016/0925-8574\(93\)90041-d](https://doi.org/10.1016/0925-8574(93)90041-d)
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202(2016), 18–27. <https://doi.org/10.1016/j.rse.2017.06.031>
- Gossweiler, B., Wesström, I., Messing, I., Romero, A. M., & Joel, A. (2019). Spatial and temporal variations in water quality and land use in a semi-arid catchment in Bolivia. *Water (Switzerland)*, 11(11). <https://doi.org/10.3390/w11112227>
- Gossweiler, B., Wesström, I., Messing, I., Villazón, M., & Joel, A. (2021). Impact of land use change on non-point source pollution in a semi-arid catchment under rapid urbanisation in Bolivia. *Water (Switzerland)*, 13(4). <https://doi.org/10.3390/w13040410>
- Gouzes, R., & Depont, G. (1990). *Evaluación de los recursos de agua y abastecimiento en agua potable de la ciudad de Cochabamba, Bolivia*. French SURECA-BRGM-SOGREAH Consortium.
- Greifeneder, F., Notarnicola, C., & Wagner, W. (2021). A machine learning-based approach for surface soil moisture estimations with google earth engine. *Remote Sensing*,

- 13(11). <https://doi.org/10.3390/rs13112099>
- Griffin, C. G., Finlay, J. C., Brezonik, P. L., Olmanson, L., & Hozalski, R. M. (2018). Limitations on using CDOM as a proxy for DOC in temperate lakes. *Water Research*, 144, 719–727. <https://doi.org/10.1016/j.watres.2018.08.007>
- Griffith, G. E., Omernik, J. M., & Azevedo, S. H. (1998). *Ecological Classification of the Western Hemisphere*.
- Guswa, A. J., Hamel, P., & Meyer, K. (2018). Curve number approach to estimate monthly and annual direct runoff. *Journal of Hydrologic Engineering*, 23(2). [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001606](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001606)
- Gutierrez, J. S., Moore, J. N., Donnelly, J. P., Dorador, C., Navedo, J. G., & Senner, N. R. (2022). Climate change and lithium mining influence flamingo abundance in the Lithium Triangle. *Proceedings of the Royal Society B: Biological Sciences*, 289(1970). <https://doi.org/10.1098/rspb.2021.2388>
- Häder, D. P., Kumar, H. D., Smith, R. C., & Worrest, R. C. (2007). Effects of solar UV radiation on aquatic ecosystems and interactions with climate change. *Photochemical and Photobiological Sciences*, 6(3), 267–285. <https://doi.org/10.1039/b700020k>
- Haines-Young, R., & Potschin-Young, M. (2018). *Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure*.
- Haines-Young, R., & Potschin, M. (2018). Common international classification of ecosystem services (CICES) V5.1 and guidance on the application of the revised structure. Available from [Www.Cices.eu](http://www.Cices.eu), January, 53. [https://cices.eu/resources/%0A%0AAvailable from www.cices.eu](https://cices.eu/resources/%0A%0AAvailable%20from%20www.cices.eu)
- Hamel, P., Chaplin-Kramer, R., Sim, S., & Mueller, C. (2015). A new approach to modeling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. *Science of The Total Environment*, 524–525, 166–177. <https://doi.org/10.1016/j.scitotenv.2015.04.027>
- Hamel, P., & Guswa, A. J. (2015). Uncertainty Analysis of the InVEST 3.0 Nutrient Model: Case Study of the Cape Fear Catchment, NC. *Hydrology and Earth System Sciences Discussions*, 11, 11001–11036. <https://doi.org/10.5194/hessd-11-11001-2014>
- Hamel, P., Valencia, J., Schmitt, R., Shrestha, M., Piman, T., Sharp, R. P., Francesconi, W., & Guswa, A. J. (2020). Modeling seasonal water yield for landscape management: Applications in Peru and Myanmar. *Journal of Environmental Management*, 270, 110792. <https://doi.org/10.1016/j.jenvman.2020.110792>
- Heathwaite, A. L., Quinn, P. F., & Hewett, C. J. M. (2005). Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. *Journal of Hydrology*, 304(1–4), 446–461. <https://doi.org/10.1016/j.jhydrol.2004.07.043>
- Hill, R., Díaz, S., Pascual, U., Stenseke, M., Molnár, Z., & Van Velden, J. (2021). Nature's contributions to people: Weaving plural perspectives. *One Earth*, 4(7), 910–915. <https://doi.org/10.1016/j.oneear.2021.06.009>
- Hjorth, P., & Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. *Futures*, 38(1), 74–92. <https://doi.org/10.1016/j.futures.2005.04.005>

- Hjorth, P., & Madani, K. (2014). Sustainability Monitoring and Assessment: New Challenges Require New Thinking. *Journal of Water Resources Planning and Management*, 140(2), 133–135. [https://doi.org/10.1061/\(asce\)wr.1943-5452.0000411](https://doi.org/10.1061/(asce)wr.1943-5452.0000411)
- Hollander, M., & Wolfe, D. A. (1973). *Nonparametric Statistical Methods*. John Wiley & Sons.
- Hsieh, W. W. (2009). *Machine Learning Methods in the Environmental Sciences: Neural Networks and Kernels*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511627217>
- Huovinen, P., Ramírez, J., Caputo, L., & Gómez, I. (2019). Mapping of spatial and temporal variation of water characteristics through satellite remote sensing in Lake Panguipulli, Chile. *Science of the Total Environment*, 679, 196–208. <https://doi.org/10.1016/j.scitotenv.2019.04.367>
- Instituto Nacional de Estadística. (2025). *Anuario Estadístico de Bolivia 2024*. Instituto Nacional de Estadística (INE). <https://anuario.ine.gob.bo/2024/index.html>
- Intergovernmental Panel on Climate Change. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use* (H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.)). Institute for Global Environmental Strategies. <https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html>
- Intergovernmental Platform on Biodiversity and Ecosystem Services. (2018). *Regional and subregional assessments of biodiversity and ecosystem services: regional and subregional assessment for Asia and the Pacific - Chapters of the regional and subregional assessment of biodiversity and ecosystem services for Asia and the Pacific*. 36(1), 13–16.
- IOCCG. (2006). Remote Sensing of Inherent Optical Properties : Fundamentals, Tests of Algorithms, and Applications. In *Reports of the International Ocean Colour Coordinating Group*, 5 (Issue 5).
- IOCCG. (2010). IOCCG Report Number 10: Atmospheric correction for remotely-sensed ocean-colour products. In *IOCCG web page* (Issue 10). <http://www.ioccg.org/reports/report10.pdf>
- Jain, A. K. (2010). Data clustering: 50 years beyond K-means. *Pattern Recognition Letters*, 31(8), 651–666. <https://doi.org/10.1016/j.patrec.2009.09.011>
- Jensen, J. R. (2014). Remote sensing of the environment. An earth resource perspective. Second edition. Pearson Prentice Hall, Upper Sadle River, New Jersey. In *Pearson Education Limited, Harlow, England* (Vol. 1).
- Jeppesen, E., Brucet, S., Naselli-Flores, L., Papastergiadou, E., Stefanidis, K., Nöges, T., Nöges, P., Attayde, J. L., Zohary, T., Coppens, J., Bucak, T., Menezes, R. F., Freitas, F. R. S., Kernan, M., Søndergaard, M., & Beklioglu, M. (2015). Ecological impacts of global warming and water abstraction on lakes and reservoirs due to changes in water level and related changes in salinity. *Hydrobiologia*, 750(1), 201–227. <https://doi.org/10.1007/s10750-014-2169-x>
- Jiménez-Navarro, I. C., Mesman, J. P., Pierson, D., Trolle, D., Nielsen, A., & Senent-Aparicio, J. (2023). Application of an integrated catchment-lake model approach for simulating effects of climate change on lake inputs and biogeochemistry. *Science of*

- the Total Environment*, 885(April). <https://doi.org/10.1016/j.scitotenv.2023.163946>
- Kadykalo, A. N., López-Rodriguez, M. D., Ainscough, J., Droste, N., Ryu, H., Ávila-Flores, G., Le Clec'h, S., Muñoz, M. C., Nilsson, L., Rana, S., Sarkar, P., Sevecke, K. J., & Harmáčková, Z. V. (2019). Disentangling 'ecosystem services' and 'nature's contributions to people.' *Ecosystems and People*, 15(1), 269–287. <https://doi.org/10.1080/26395916.2019.1669713>
- Karger, D. N., Conrad, O., Böhrner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., Zimmermann, N. E., Linder, H. P., & Kessler, M. (2021). *CHELSEA climatologies at high resolution for the Earth's land surface areas V2.1*. <https://doi.org/10.16904/envdat.228>
- Karimi, H., Staudhammer, C. L., Therrell, M. D., Kleindl, W. J., Mungai, L. M., Amanambu, A. C., & Jones, C. N. (2025). Mapping Tradeoffs and Synergies in Ecosystem Services as a Function of Forest Management. *Land*, 14(8), 1–26. <https://doi.org/10.3390/land14081591>
- Kates, R. W., Clark, W. C., Corell, R., Hall, M., Jaeger, C. C., Lowe, I., James, J., Schellnhuber, H. J., Bolin, B., Dickson, M., Faucheux, S., Gallopin, G. C., Huntley, B., Jäger, J., Jodha, N. S., Kaspersen, E., Mabogunje, A., Matson, P., Iii, B. M., ... Riordan, T. O. (2001). *Belfer Center for Science & International Affairs Sustainability Science*. 292(December 2000), 641–642.
- Kaval, P. (2019). Integrated catchment management and ecosystem services: A twenty-five year overview. *Ecosystem Services*, 37(March), 100912. <https://doi.org/10.1016/j.ecoser.2019.100912>
- Keeler, B. L., Polasky, S., Brauman, K. A., Johnson, K. A., Finlay, J. C., O'Neill, A., Kovacs, K., & Dalzell, B. (2012). Linking water quality and well-being for improved assessment and valuation of ecosystem services. *Proceedings of the National Academy of Sciences*, 109(45), 18619–18624. <https://doi.org/10.1073/pnas.1215991109>
- Kirk, J. T. O. (2011). *Light and Photosynthesis in Aquatic Ecosystems* (3rd ed.). Cambridge University Press.
- Köppen, W., & Geiger, R. (1936). Das Geographische System der Klimate. In W. Köppen & R. Geiger (Eds.), *Handbuch der Klimatologie: Vol. Band I* (Issue c).
- Kreibich, H., Sivapalan, M., AghaKouchak, A., Addor, N., Aksoy, H., Arheimer, B., Arnbjerg-Nielsen, K., Vail-Castro, C., Cudennec, C., Madruga de Brito, M., Di Baldassarre, G., Finger, D. C., Fowler, K., Knoben, W., Krueger, T., Liu, J., Macdonald, E., McMillan, H., MENDIONDO, E. M., ... Blöschl, G. (2025). Panta Rhei: a decade of progress in research on change in hydrology and society. *Hydrological Sciences Journal*, 70(7), 1210–1236. <https://doi.org/10.1080/02626667.2025.2469762>
- Kremen, C. (2005). Managing ecosystem services: What do we need to know about their ecology? *Ecology Letters*, 8(5), 468–479. <https://doi.org/10.1111/j.1461-0248.2005.00751.x>
- Krishnaraj, A., & Honnasiddaiah, R. (2023). Multi-spatial-scale land/use land cover influences on seasonally dominant water quality along Middle Ganga Basin. *Environmental Monitoring and Assessment*, 195(12). <https://doi.org/10.1007/s10661-023-12059-y>
- Kruskal, W. H., & Wallis, W. A. (1952). Use of Ranks in One-Criterion Variance Analysis.

- Journal of the American Statistical Association*, 47(260), 583–621. <https://doi.org/10.1080/01621459.1952.10483441>
- Kuiper, J. J. (2023). A plea for more freshwater experts in IPBES. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 33(6), 1162–1164. <https://doi.org/10.1002/aqc.3956>
- La Notte, A., D'Amato, D., Mäkinen, H., Paracchini, M. L., Liqueste, C., Egoh, B., Geneletti, D., & Crossman, N. D. (2017). Ecosystem services classification: A systems ecology perspective of the cascade framework. *Ecological Indicators*, 74, 392–402. <https://doi.org/10.1016/j.ecolind.2016.11.030>
- Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, 304(5677), 1623–1627. <https://doi.org/10.1126/science.1097396>
- Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., & Thomas, C. J. (2012). Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustainability Science*, 7(SUPPL. 1), 25–43. <https://doi.org/10.1007/s11625-011-0149-x>
- Lee, S. W., Hwang, S. J., Lee, S. B., Hwang, H. S., & Sung, H. C. (2009). Landscape ecological approach to the relationships of land use patterns in watersheds to water quality characteristics. *Landscape and Urban Planning*, 92(2), 80–89. <https://doi.org/10.1016/j.landurbplan.2009.02.008>
- Lehner, B., Messenger, M. L., Korver, M. C., & Linke, S. (2022). Global hydro-environmental lake characteristics at high spatial resolution. *Scientific Data*, 9(1). <https://doi.org/10.1038/s41597-022-01425-z>
- Li, S., Zhang, J., Jiang, P., & Zhang, L. (2022). Linking land use with riverine water quality: A multi-spatial scale analysis relating to various riparian strips. *Frontiers in Environmental Science*, 10. <https://doi.org/10.3389/fenvs.2022.1013318>
- Li, Y., Wang, G., Sun, S., Chang, R., Wang, T., Hu, Z., Xu, F., Yang, Y., & Song, C. (2025). Net carbon dioxide sequestration by large alkaline lakes dominates the carbon exchange of Qinghai-Tibet Plateau lakes. *Communications Earth and Environment*, 6(1), 1–12. <https://doi.org/10.1038/s43247-025-02884-z>
- Liaw, A., & Wiener, M. (2002). Classification and Regression by RandomForest. *R News*, 2(3), 18–22.
- Likert, R. (1932). A Technique for the Measurement of Attitudes. *Archives of Psychology*, 22(140), 1–55.
- Lillesand, T. M., Johnson, W. L., & Deuell, R. L. (1983). Use of landsat data to predict the trophic state of Minnesota lakes. *Photogrammetric Engineering and Remote Sensing*, 49(2), 219–229.
- Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2015). Remote sensing and image interpretation. In *Remote sensing and image interpretation*. (7th ed.). John Wiley & Sons. <https://doi.org/10.2307/634969>
- Linke, S., Lehner, B., Ouellet Dallaire, C., Ariwi, J., Grill, G., Anand, M., Beames, P., Burchard-Levine, V., Maxwell, S., Moidu, H., Tan, F., & Thieme, M. (2019). Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. *Scientific Data*, 6(1), 1–15. <https://doi.org/10.1038/s41597-019-0300-6>
- Liu, J., Zhang, X., Xia, J., Wu, S., She, D., & Zou, L. (2016). Characterizing and explaining

- spatio-temporal variation of water quality in a highly disturbed river by multi-statistical techniques. *SpringerPlus*, 5(1). <https://doi.org/10.1186/s40064-016-2815-z>
- Locke, K. A. (2024a). Impacts of land use/land cover on water quality: A contemporary review for researchers and policymakers. In *Water Quality Research Journal* (Vol. 59, Issue 2, pp. 89–106). IWA Publishing. <https://doi.org/10.2166/wqrj.2024.002>
- Locke, K. A. (2024b). Modelling relationships between land use and water quality using statistical methods: A critical and applied review. In *Journal of Environmental Management* (Vol. 362). Academic Press. <https://doi.org/10.1016/j.jenvman.2024.121290>
- Lundberg, S. M., & Lee, S. (2017). *A Unified Approach to Interpreting Model Predictions. Section 2*, 1–10.
- MacQueen, J. (1967). Some Methods for Classification and Analysis of Multivariate Observations. *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability*, 1, 281–297.
- Main-Knorn, M., Pflug, B., Louis, J., Debaecker, V., Müller-Wilm, U., & Gascon, F. (2017). *Sen2Cor for Sentinel-2. October*, 3. <https://doi.org/10.1117/12.2278218>
- Mandle, L., & others. (2024). *Accelerating Biodiversity and Ecosystem Reporting: Feasible and Cost-Effective Reporting With AI, Earth Observation, & Ecosystem Science*. <https://naturalcapitalproject.stanford.edu>
- Márquez, L. A. M., Rezende, E. C. N., Machado, K. B., Nascimento, E. L. M. do, Castro, J. D. ar. B., & Nabout, J. C. (2023). Trends in valuation approaches for cultural ecosystem services: A systematic literature review. *Ecosystem Services*, 64(November). <https://doi.org/10.1016/j.ecoser.2023.101572>
- Martínez-Alier, J., & Muradian, R. (2015). Handbook of Ecological Economics. In *Handbook of Ecological Economics*. <https://doi.org/10.4337/9781783471416>
- Mashala, M. J., Dube, T., Mudereri, B. T., Ayisi, K. K., & Ramudzuli, M. R. (2023). A Systematic Review on Advancements in Remote Sensing for Assessing and Monitoring Land Use and Land Cover Changes Impacts on Surface Water Resources in Semi-Arid Tropical Environments. *Remote Sensing*, 15(16). <https://doi.org/10.3390/rs15163926>
- Massicotte, P., Asmala, E., Stedmon, C., & Markager, S. (2017). Global distribution of dissolved organic matter along the aquatic continuum: Across rivers, lakes and oceans. *Science of the Total Environment*, 609, 180–191. <https://doi.org/10.1016/j.scitotenv.2017.07.076>
- Max-Neef, M. (2005). Fundamentos de la transdisciplinaridad. *Ecological Economics*, 53, 5–16.
- Max Neef, M. (2016). Philosophy of Ecological Economics. *International Journal of Economics & Management Sciences*, 5(5). <https://doi.org/10.4172/2162-6359.1000366>
- McBroom, M. W., Beasley, R. S., Chang, M., & Ice, G. G. (2008). Storm runoff and sediment losses from forest clearcutting and stand re-establishment with best management practices in East Texas, USA. *Hydrological Processes*, 22(10), 1509–1522. <https://doi.org/10.1002/hyp.6703>
- McFeeters, S. K. (1996). The use of the Normalized Difference Water Index (NDWI) in the

- delineation of open water features. *International Journal of Remote Sensing*, 17(7), 1425–1432.
- McInnes, R. J., & Everard, M. (2017). Rapid Assessment of Wetland Ecosystem Services (RAWES): An example from Colombo, Sri Lanka. *Ecosystem Services*, 25, 89–105. <https://doi.org/10.1016/j.ecoser.2017.03.024>
- McKinney, W. (2010). Data structures for statistical computing in Python. *Proceedings of the 9th Python in Science Conference*, 445, 51–56.
- Mehmood, T., Liland, K. H., Snipen, L., & Sæbø, S. (2012). A Review of Variable Selection Methods in Partial Least Squares Regression. *Chemometrics and Intelligent Laboratory Systems*, 118, 62–69. <https://doi.org/10.1016/j.chemolab.2012.07.010>
- Mello, K. de, Taniwaki, R. H., Paula, F. R. de, Valente, R. A., Randhir, T. O., Macedo, D. R., Leal, C. G., Rodrigues, C. B., & Hughes, R. M. (2020). Multiscale land use impacts on water quality: Assessment, planning, and future perspectives in Brazil. In *Journal of Environmental Management* (Vol. 270). Academic Press. <https://doi.org/10.1016/j.jenvman.2020.110879>
- Mello, K. de, Valente, R. A., Randhir, T. O., dos Santos, A. C. A., & Vettorazzi, C. A. (2018). Effects of land use and land cover on water quality of low-order streams in Southeastern Brazil: Watershed versus riparian zone. *Catena*, 167, 130–138. <https://doi.org/10.1016/j.catena.2018.04.027>
- Merritt, W. S., Letcher, R. A., & Jakeman, A. J. (2003). A review of erosion and sediment transport models. *Environmental Modelling & Software*, 18(8–9), 761–799. [https://doi.org/10.1016/S1364-8152\(03\)00078-1](https://doi.org/10.1016/S1364-8152(03)00078-1)
- Meza-Duman, R., Hermoza-Gutierrez, M., Maldonado, I., & Salas-Mercado, D. (2022). *Percepción Social de la Calidad del Agua y la Expansión Territorial de la Minería en Ollachea, Puno, Perú Social Perception of Water Quality and Territorial Expansion of Mining in Ollachea, Puno, Peru*. 13, 16–28.
- Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: Synthesis*. Island Press.
- Ministerio de Medio Ambiente y Agua (MMAyA). (2023). *Balance hídrico, Sistema de Información de Agua y Recursos Hídricos*. <http://vibh.mmaya.gob.bo/vibh/database/dashboard>
- Mirmazloumi, S. M., Kakooei, M., Mohseni, F., Ghorbanian, A., Amani, M., Crosetto, M., & Monserrat, O. (2022). ELULC-10, a 10 m European Land Use and Land Cover Map Using Sentinel and Landsat Data in Google Earth Engine. *Remote Sensing*, 14(13). <https://doi.org/10.3390/rs14133041>
- Mishan, E. J. (1967). *The Costs of Economic Growth*. Staples Press.
- Mishra, S., & Mishra, D. R. (2012). Normalized difference chlorophyll index: A novel model for remote estimation of chlorophyll-a concentration in turbid productive waters. *Remote Sensing of Environment*, 117(February), 394–406. <https://doi.org/10.1016/j.rse.2011.10.016>
- Mobley, C. D. (1999). Estimation of the remote-sensing reflectance from above-surface measurements. *Applied Optics*, 38(36), 7442. <https://doi.org/10.1364/ao.38.007442>
- Mobley, C. D., Werdell, J., Franz, B., Ahmad, Z., & Bailey, S. (2016). Atmospheric correction for satellite ocean color radiometry. *A Tutorial and Documentation NASA*

- Ocean Biology Processing Group, June, 1–73.
- Molnar, C. (2022). *Interpretable Machine Learning: A Guide for Making Black Box Models Explainable* (2nd ed.). <https://christophm.github.io/interpretable-ml-book/>
- Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaeffli, B., Arheimer, B., Boegh, E., Schymanski, S. J., ... Belyaev, V. (2013). “Panta Rhei—Everything Flows”: Change in hydrology and society—The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal*, 58(6), 1256–1275. <https://doi.org/10.1080/02626667.2013.809088>
- Mooney, H. A. (1983). What Is the Biosphere Worth? *BioScience*, 33(8), 486–487. <https://doi.org/10.2307/1309140>
- Moran, P. A. P. (1950). A Test for the Serial Independence of Residuals. *Biometrika*, 37(1–2), 178–181. <https://doi.org/10.1093/biomet/37.1-2.178>
- Morin, E., Herrault, P. A., Guinard, Y., Grandjean, F., & Bech, N. (2022). The promising combination of a remote sensing approach and landscape connectivity modelling at a fine scale in urban planning. *Ecological Indicators*, 139. <https://doi.org/10.1016/j.ecolind.2022.108930>
- Mutanga, O., Adam, E., & Cho, M. A. (2012). High density biomass estimation for wetland vegetation using worldview-2 imagery and random forest regression algorithm. *International Journal of Applied Earth Observation and Geoinformation*, 18(1), 399–406. <https://doi.org/10.1016/j.jag.2012.03.012>
- Naderian, D., Noori, R., Heggy, E., Bateni, S. M., Bhattarai, R., Nohegar, A., & Sharma, S. (2024). A water quality database for global lakes. *Resources, Conservation and Recycling*, 202(September 2023), 107401. <https://doi.org/10.1016/j.resconrec.2023.107401>
- NASA Socioeconomic Data and Applications Center (SEDAC). (2023). *Gridded Population of the World (GPW), v4.11: Population Density*. <https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11>
- National Academies of Sciences. (2021). *Progress, Challenges, and Opportunities for Sustainability Science: Proceedings of a Workshop—in Brief* (P. Whitacre & E. Kameyama (Eds.)). The National Academies Press. <https://doi.org/10.17226/26104>
- Natural Capital Project. (2018). *InVEST 3.5 User's Guide*. <https://naturalcapitalproject.stanford.edu/software/invest>
- Natural Resources Conservation Service. (2007). *National Engineering Handbook*. <https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1043063>
- Navarro, G., & Ferreira, W. (2007). *Mapa de vegetación de Bolivia a escala 1:250.000*. The Nature Conservancy (TNC), RUMBOL.
- Navarro, G., & Maldonado, M. (2002). *Geografía Ecológica de Bolivia: Vegetación y Ambientes Acuáticos* (First). Centro de Ecología Simón I. Patiño.
- Nearing, G. S., Kratzert, F., Sampson, A. K., Pelissier, C. S., Klotz, D., Frame, J. M., Prieto, C., & Gupta, H. V. (2021). What Role Does Hydrological Science Play in the Age of Machine Learning? *Water Resources Research*, 57(3). <https://doi.org/10.1029/2020WR028091>

- Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D. R., Chan, K. M. A., Daily, G. C., Goldstein, J., Kareiva, P., Lonsdorf, E., Naidoo, R., Ricketts, T. H., & Shaw, R. (2009). Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment*, 7(1), 4–11. <https://doi.org/10.1890/080023>
- Neumann-Redlin, C. M., Renner, S., & Torres, J. (2000). Hidrogeología del Valle Central de Cochabamba, Bolivia. *Águas Subterráneas*. <https://aguassubterrneas.abas.org/asubterrneas/article/view/24016>
- Nordhaus, W. D. (1973). World Dynamics: Measurement without Data. *Economic Journal*, 83(332), 1156–1183. <https://doi.org/10.2307/2230836>
- Nordhaus, W. D. (1977). Economic Growth and Climate: The Carbon Dioxide Problem. *American Economic Review Papers and Proceedings*, 67(1), 341–346.
- Nordhaus, W. D., & Tobin, J. (1972). Is Growth Obsolete? In *Economic Growth* (pp. 1–80). National Bureau of Economic Research.
- Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., Bednarek, A. T., Bennett, E. M., Biggs, R., de Bremond, A., Campbell, B. M., Canadell, J. G., Carpenter, S. R., Folke, C., Fulton, E. A., Gaffney, O., Gelcich, S., Jouffray, J. B., Leach, M., ... Österblom, H. (2020). Principles for knowledge co-production in sustainability research. *Nature Sustainability*, 3(3), 182–190. <https://doi.org/10.1038/s41893-019-0448-2>
- O'Brien, K. (2012). Global environmental change II: From adaptation to deliberate transformation. *Progress in Human Geography*, 36(5), 667–676. <https://doi.org/10.1177/0309132511425767>
- O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability*, 1(2), 88–95. <https://doi.org/10.1038/s41893-018-0021-4>
- Olden, J. D., Lawler, J. J., & Poff, N. L. (2008). Machine Learning Methods Without Tears: A Primer for Ecologists. *The Quarterly Review of Biology*, 83(2), 171–193. <https://doi.org/10.1086/587826>
- Oliveira Santos, V., Guimarães, B. M. D. M., Lima Neto, I. E., Souza Filho, F. de A., Costa Rocha, P. A., Van Griensven Thé, J., & Gharabaghi, B. (2023). Chlorophyll-a Estimation in 149 Tropical Semi-Arid Reservoirs Using Remote Sensing and Machine Learning. *Preprints*. <http://dx.doi.org/10.20944/preprints202312.1854.v1>
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939), 419–422.
- Ouma, Y. O., Noor, K., & Herbert, K. (2020). Modelling Reservoir Chlorophyll- a, TSS, and Turbidity Using Sentinel-2A MSI and Landsat-8 OLI Satellite Sensors with Empirical Multivariate Regression. *Journal of Sensors*, 2020. <https://doi.org/10.1155/2020/8858408>
- Pahlevan, N., Mangin, A., Balasubramanian, S. V., Smith, B., Alikas, K., Arai, K., Barbosa, C., Bélanger, S., Binding, C., Bresciani, M., Giardino, C., Gurlin, D., Fan, Y., Harmel, T., Hunter, P., Ishikaza, J., Kratzer, S., Lehmann, M. K., Ligi, M., ... Warren, M. (2021). ACIX-Aqua: A global assessment of atmospheric correction methods for Landsat-8 and Sentinel-2 over lakes, rivers, and coastal waters. *Remote Sensing of*

- Environment*, 258(March). <https://doi.org/10.1016/j.rse.2021.112366>
- Pahlevan, N., Sarkar, S., Franz, B. A., Balasubramanian, S. V., & He, J. (2017). Sentinel-2 MultiSpectral Instrument (MSI) data processing for aquatic science applications: Demonstrations and validations. *Remote Sensing of Environment*, 201(May), 47–56. <https://doi.org/10.1016/j.rse.2017.08.033>
- Pal, M. (2005). Random Forest Classifier for Remote Sensing Classification. *International Journal of Remote Sensing*, 26(1), 217–222. <https://doi.org/10.1080/01431160412331269698>
- Paná, S., Marinelli, M. V., Bonansea, M., Ferral, A., Valente, D., Camacho Valdez, V., & Petrosillo, I. (2024). The multiscale nexus among land use-land cover changes and water quality in the Suquía River Basin, a semi-arid region of Argentina. *Scientific Reports*, 14(1), 1–14. <https://doi.org/10.1038/s41598-024-53604-0>
- Panagos, P., Borrelli, P., Meusburger, K., Yu, B., Klik, A., Lim, K. J., Yang, J. E., Ni, J., Miao, C., Chattopadhyay, N., Sadeghi, S. H., & others. (2017). Global rainfall erosivity assessment based on high-temporal resolution rainfall records. *Scientific Reports*, 7, 4175. <https://doi.org/10.1038/s41598-017-04282-8>
- Panagos, P., Hengl, T., Wheeler, I., Marcinkowski, P., Rukeza, M. B., Yu, B., Yang, J. E., Miao, C., Chattopadhyay, N., Sadeghi, S. H., Levi, Y., Erpul, G., Birkel, C., Hoyos, N., Oliveira, P. T. S., Bonilla, C. A., Nel, W., Al Dashti, H., Fenta, A. A., ... others. (2023). Global rainfall erosivity database (GloREDa) and monthly R-factor data at 1\,km spatial resolution. *Data in Brief*, 50, 109482. <https://doi.org/10.1016/j.dib.2023.109482>
- Pandeya, B., Buytaert, W., Zulkafli, Z., Karpouzoglou, T., Mao, F., & Hannah, D. M. (2016). A comparative analysis of ecosystem services valuation approaches for application at the local scale and in data scarce regions. *Ecosystem Services*, 22, 250–259. <https://doi.org/https://doi.org/10.1016/j.ecoser.2016.10.015>
- Pang, Z., Zhou, Z., Fu, J., Jiang, W., Qin, X., & Sun, M. (2025). Deep learning-based remote sensing retrieval of inland water quality: A review. *Journal of Hydrology: Regional Studies*, 61(September), 102759. <https://doi.org/10.1016/j.ejrh.2025.102759>
- Passet, R. (1979). *L'Économique et le Vivant*. Payot.
- Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., & Duchesnay, É. (2011). Scikit-learn: Machine learning in Python. *Journal of Machine Learning Research*, 12, 2825–2830.
- Pekel, J.-F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, 540, 418–422. <https://doi.org/10.1038/nature20584>
- Pelletier, J. D. (2012). A spatially distributed model for the long-term suspended sediment discharge and delivery ratio of drainage basins. *Journal of Geophysical Research: Earth Surface*, 117, F02028. <https://doi.org/10.1029/2011JF002129>
- Perevochtchikova, M., De la Mora-De la Mora, G., Hernández Flores, J. Á., Marín, W., Langle Flores, A., Ramos Bueno, A., & Rojo Negrete, I. A. (2019). Systematic review of integrated studies on functional and thematic ecosystem services in Latin America, 1992–2017. *Ecosystem Services*, 36(February), 100900.

- <https://doi.org/10.1016/j.ecoser.2019.100900>
- Prado, P. E., Modenutti, B., Aranguren-Riaño, N., Balseiro, E., Samanez, I., Campero, M., Fernández, C. E., Rivera-Rondon, C. A., Carvajal-Vallejos, F. M., López-Paría, D., Herrera-Martínez, Y., de los Ríos-Escalante, P., & Steinitz-Kannan, M. (2024). Andean Lakes: a proposal for lake districts. *Inland Waters*, 14(4), 369–387. <https://doi.org/10.1080/20442041.2024.2379147>
- Prado, P. E., Oporto, C. G., Jönsson, K., Rejas, D., Martinez, V., & Persson, K. M. (2025). Influence of land use/land cover on stream water quality in two watersheds in the central Andes of Bolivia: An optimised methodology. *Ecological Indicators*, 178(June). <https://doi.org/10.1016/j.ecolind.2025.113984>
- Prado, P. E., Rejas, D., Oporto, C. G., Jönsson, K., Decsi, B., & Persson, K. M. (2026). Freshwater Ecosystem Services valuation in a Region of the Central Andes of Bolivia: a novel framework. [Manuscript Submitted for Publication]. Department of Building and Environmental Technology, Lund University.
- Prado, P. E., Rejas, D., Oporto, C. G., Jönsson, K., Murphy, K. R., & Persson, K. M. (2026). Unveiling Small High Andean Lakes: A Multi-Sensor Framework for Monitoring Trophic State, Dissolved Organic Carbon, and Hydroclimatic Drivers in Central Andes of Bolivia. [Manuscript Submitted for Publication]. Department of Building and Environmental Technology, Lund University.
- Pratt, B., & Chang, H. (2012). Effects of land cover, topography, and built structure on seasonal water quality at multiple spatial scales. *Journal of Hazardous Materials*, 209–210, 48–58. <https://doi.org/10.1016/j.jhazmat.2011.12.068>
- Preisendorfer, R. W. (1958). *On the existence of characteristic diffuse light in natural waters*.
- Preisendorfer, R. W. (1971). General theory of radiative transfer across the random atmosphere-ocean interface. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 11(6), 723–737.
- Preisendorfer, R. W. (1976). *Hydrologic optics*. US Department of Commerce, National Oceanic and Atmospheric Administration~....
- Preisendorfer, R. W., & Tyler, J. E. (1958). *The measurement of light in natural waters; radiometric concepts and optical properties*.
- Python Software Foundation. (2023). *Python Language Reference, version 3.1* (3.11.4). <http://www.python.org>
- Quenta-Herrera, E., Crespo-Pérez, V., Mark, B. G., Gonzales, A. L., & Kulonen, A. (2022). Mountain freshwater ecosystems and protected areas in the tropical Andes: insights and gaps for climate change adaptation. *Environmental Conservation*, 49(1), 17–26. <https://doi.org/10.1017/S0376892921000382>
- Quenta, E., Molina-Rodriguez, J., Gonzales, K., Rebaudo, F., Casas, J., Jacobsen, D., & Dangles, O. (2016). Direct and indirect effects of glaciers on aquatic biodiversity in high Andean peatlands. *Global Change Biology*, 22(9), 3196–3205. <https://doi.org/10.1111/gcb.13310>
- R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.r-project.org/>
- Rana, R., Kalia, A., Boora, A., Alfaisal, F. M., Alharbi, R. S., Berwal, P., Alam, S., Khan,

- M. A., & Qamar, O. (2023). Artificial Intelligence for Surface Water Quality Evaluation, Monitoring and Assessment. *Water*, 15(22). <https://doi.org/10.3390/w15223919>
- Randhir, T. O., & Tsvetkova, O. (2011). Spatiotemporal dynamics of landscape pattern and hydrologic process in watershed systems. *Journal of Hydrology*, 404(1–2), 1–12. <https://doi.org/10.1016/j.jhydrol.2011.03.019>
- Raworth, K. (2012). A safe and just space for humanity: can we live within the doughnut? Oxfam Discussion Paper. *State of the World 2003: Progress Towards a Sustainable Society*: 20th Edition, 1–240. www.oxfam.org/grow%0Awww.oxfam.org/grow%0Awww.oxfam.org/grow%0Ahttps://www-cdn.oxfam.org/s3fs-public/file_attachments/dp-a-safe-and-just-space-for-humanity-130212-en_5.pdf
- Raworth, K. (2017). *Raworth Doughnut Economics*. <https://www.kateraworth.com/doughnut/>
- Reckhow, K. H., Beaulac, M. N., & Simpson, J. T. (1980). *Modeling Phosphorus Loading and Lake Response under Uncertainty: A Manual and Compilation of Export Coefficients* (Issue EPA 440/5-80-011).
- Redhead, J. W., May, L., Oliver, T. H., Hamel, P., Sharp, R., & Bullock, J. M. (2018). National scale evaluation of the InVEST nutrient retention model in the United Kingdom. *Science of the Total Environment*, 610–611, 666–677. <https://doi.org/10.1016/j.scitotenv.2017.08.092>
- Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., & Prabhat. (2019). Deep learning and process understanding for data-driven Earth system science. *Nature*, 566(7743), 195–204. <https://doi.org/10.1038/s41586-019-0912-1>
- Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., & Yoder, D. C. (1997). *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*. U.S. Department of Agriculture.
- Renard, K. G., & Freimund, J. R. (1994). Using monthly precipitation data to estimate the R-factor in the revised USLE. *Journal of Hydrology*, 157, 287–306. [https://doi.org/10.1016/0022-1694\(94\)90110-4](https://doi.org/10.1016/0022-1694(94)90110-4)
- Renner, S., & Velasco, C. (2000). *Geology and hydrogeology of the Central Valley of Cochabamba*. German Bolivian Agreement on Groundwater (CABAS).
- Richardson, J. S., & Danehy, R. J. (2007). A Synthesis of the Ecology of Headwater Streams and their Riparian Zones in Temperate Forests. *Forest Science*, 53(2), 131–147. <https://doi.org/10.1093/forestscience/53.2.131>
- Rimer, A. E., Nissen, J. A., & Reynolds, D. E. (1978). Characterization and impact of stormwater runoff from various land cover types. *Journal of the Water Pollution Control Federation*, 50(2), 252–264.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., ... Foley, J. A. (2009). A safe operating space for humanity. *Nature*, 461, 472–475. <https://doi.org/10.1038/461472a>

- Ross, C., Prihodko, L., Anchang, J., Kumar, S., Ji, W., Hanan, N. P., & others. (2018). HYSOGs250m, global gridded hydrologic soil groups for curve-number-based runoff modeling. *Scientific Data*, 5, 180091. <https://doi.org/10.1038/sdata.2018.91>
- Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. *Third ERTS-1 Symposium*, 1, 309–317.
- Royston, J. P. (1982). An Extension of Shapiro and Wilk's W Test for Normality to Large Samples. *Applied Statistics*, 31(2), 115. <https://doi.org/10.2307/2347973>
- Running, S., Mu, Q., & Zhao, M. (2021). *MOD16A2/A3 Terra/Aqua Net Evapotranspiration (ET/PET) Product User's Guide Collection 6.1*. https://lpdaac.usgs.gov/documents/93/MOD16_ATBD.pdf
- Sachs, I. (1977). Environment and Styles of Development. *Economic and Political Weekly*, 12(38), 1489–1495.
- Sánchez Valdivia, A., De Stefano, L. G., Ferraro, G., Gianello, D., Ferral, A., Dogliotti, A. I., Reissig, M., Gereá, M., Queimaliños, C., & Pérez, G. L. (2024). Characterizing Chromophoric Dissolved Organic Matter Spatio-Temporal Variability in North Andean Patagonian Lakes Using Remote Sensing Information and Environmental Analysis. *Remote Sensing*, 16(21). <https://doi.org/10.3390/rs16214063>
- Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, 413(6856), 591–596. <https://doi.org/10.1038/35098000>
- Schiassi, E., Furfaro, R., Kargel, J. S., Watson, C. S., Shugar, D. H., & Haritashya, U. K. (2019). GLAM Bio-Lith RT: A Tool for Remote Sensing Reflectance Simulation and Water Components Concentration Retrieval in Glacial Lakes. *Frontiers in Earth Science*, 7(October). <https://doi.org/10.3389/feart.2019.00267>
- Schmidt, K., Walz, A., & Martín-López, B. (2017). Testing socio-cultural valuation methods of ecosystem services to explain land use preferences. *Ecosystem Services*, 26, 270–288. <https://doi.org/10.1016/j.ecoser.2017.07.002>
- Schorr, B., Braig, M., Fritz, B., & Schütt, B. (2021). The global knowledge value chain on sustainability: Addressing fragmentations through international academic partnerships. *Sustainability (Switzerland)*, 13(17). <https://doi.org/10.3390/su13179930>
- Scowen, M., Athanasiadis, I. N., Bullock, J. M., Eigenbrod, F., & Willcock, S. (2021). The current and future uses of machine learning in ecosystem service research. *Science of The Total Environment*, 799, 149263. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.149263>
- Sekercioglu, C. H., Boyce, M. S., Tschardtke, T., Davidar, P., & Kremen, C. (2010). Ecosystem functions and services. *Conservation Biology for All*. <https://doi.org/10.1093/acprof:oso/9780199554232.003.0004>
- Senay, G. B., Parrish, G. E. L., Schauer, M., Friedrichs, M., Khand, K., Boiko, O., Kagone, S., Dittmeier, R., Arab, S., & Ji, L. (2023). Improving the Operational Simplified Surface Energy Balance (SSEBop) Evapotranspiration Model Using the Forcing and Normalizing Operation (FANO). *Remote Sensing*, 15(1), 260. <https://doi.org/10.3390/rs15010260>
- Seppelt, R., Fath, B., Burkhard, B., Fisher, J. L., Grêt-Regamey, A., Lautenbach, S., Pert, P., Hotes, S., Spangenberg, J., Verburg, P. H., & Van Oudenhoven, A. P. E. (2012).

- Form follows function? Proposing a blueprint for ecosystem service assessments based on reviews and case studies. *Ecological Indicators*, 21, 145–154. <https://doi.org/10.1016/j.ecolind.2011.09.003>
- Servicio Nacional de Áreas Protegidas (SERNAP). (2016). *Mapa de áreas protegidas nacionales de Bolivia*. <https://geo.gob.bo>
- Servicio Nacional de Meteorología e Hidrología (SENAMHI). (2025). *Información Nacional de Datos Hidrometeorológicos*. <https://senamhi.gob.bo/index.php/are>
- Shelestov, A., Lavreniuk, M., Kussul, N., Novikov, A., & Skakun, S. (2017). Exploring Google earth engine platform for big data processing: Classification of multi-temporal satellite imagery for crop mapping. *Frontiers in Earth Science*, 5, 1–10. <https://doi.org/10.3389/feart.2017.00017>
- Shen, C. (2018). A Transdisciplinary Review of Deep Learning Research and Its Relevance for Water Resources Scientists. *Water Resources Research*, 54(11), 8558–8593. <https://doi.org/10.1029/2018WR022643>
- Shen, H., Zhou, M., Li, T., & Zeng, C. (2019). Integration of remote sensing and social sensing data in a deep learning framework for hourly urban PM_{2.5} mapping. *International Journal of Environmental Research and Public Health*, 16(21). <https://doi.org/10.3390/ijerph16214102>
- Sherrouse, B. C., Semmens, D. J., & Clement, J. M. (2014). An application of Social Values for Ecosystem Services (SolVES) to three national forests in Colorado and Wyoming. *Ecological Indicators*, 36, 68–79. <https://doi.org/10.1016/j.ecolind.2013.07.008>
- Shi, P., Zhang, Y., Li, Z., Li, P., & Xu, G. (2017). Influence of land use and land cover patterns on seasonal water quality at multi-spatial scales. *Catena*, 151, 182–190. <https://doi.org/10.1016/j.catena.2016.12.017>
- Simons, G. W. H., Koster, R., & Droogers, P. (2020). *HiHydroSoil v2.0 – High Resolution Soil Maps of Global Hydraulic Properties* (Issue Report 213).
- Sivapalan, M., & Blöschl, G. (2015). Time scale interactions and the coevolution of humans and water. *Water Resources Research*, 51(9), 6988–7022.
- Sivapalan, M., Savenije, H. H. G., Blöschl, G., & others. (2012). Socio-hydrology: A new science of people and water. *Hydrological Processes*, 26(8), 1270–1276.
- Soranno, P. A., Cheruvilil, K. S., Webster, K. E., Bremigan, M. T., Wagner, T., & Stow, C. A. (2010). Using landscape limnology to classify freshwater ecosystems for multi-ecosystem management and conservation. *BioScience*, 60(6), 440–454. <https://doi.org/10.1525/bio.2010.60.6.8>
- Spash, C. L. (2015). Bulldozing biodiversity: The economics of offsets and trading-in Nature. *Biological Conservation*, 192, 541–551. <https://doi.org/10.1016/j.biocon.2015.07.037>
- Spash, C. L. (Ed.). (2017). *Routledge Handbook of Ecological Economics: Nature and Society* (1st ed.). Routledge. <https://doi.org/10.4324/9781315679747>
- Spash, C. L. (2020). A tale of three paradigms: Realising the revolutionary potential of ecological economics. *Ecological Economics*, 169(October 2019), 106518. <https://doi.org/10.1016/j.ecolecon.2019.106518>
- Spencer, R. G. M., Butler, K. D., & Aiken, G. R. (2012). Dissolved organic carbon and

- chromophoric dissolved organic matter properties of rivers in the USA. *Journal of Geophysical Research: Biogeosciences*, 117(3).
<https://doi.org/10.1029/2011JG001928>
- GB3838-2002: Environmental Quality Standards for Surface Water, (2002).
- Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855. <https://doi.org/10.1126/science.1259855>
- Stehman, S. V. (1997). Selecting and Interpreting Measures of Thematic Classification Accuracy. *Remote Sensing of Environment*, 77–89.
- Stern, N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge University Press.
- Taheri Dehkordi, A., Dazi, M., Naghibi, A., & Hashemi, H. (2026). WQEye (v1): A Python-based software for machine learning-based retrieval of water quality parameters from Sentinel-2 and Landsat-8/9 remote sensing data aided by Google Earth Engine. *Ecological Informatics*, 95(October 2025), 103692.
<https://doi.org/10.1016/j.ecoinf.2026.103692>
- Tan, W., Zhang, J., Wu, J., Lan, H., Liu, X., Xiao, K., Wang, L., Lin, H., Sun, G., & Guo, P. (2022). Application of CNN and Long Short-Term Memory Network in Water Quality Predicting. *Intelligent Automation and Soft Computing*, 34(3), 1943–1958.
<https://doi.org/10.32604/iasc.2022.029660>
- Tanaka, M. O., de Souza, A. L. T., Moschini, L. E., & de Oliveira, A. K. (2016). Influence of watershed land use and riparian characteristics on biological indicators of stream water quality in southeastern Brazil. *Agriculture, Ecosystems and Environment*, 216, 333–339. <https://doi.org/10.1016/j.agee.2015.10.016>
- Tasser, E., Kuhlmann, K., Mwanza, M. W., Schermer, M., Tappeiner, U., Tembo, G., Zoderer, B. M., & Schirpke, U. (2025). A comparative analysis of ecosystem services perceptions across two regions in Eastern Africa and Central Europe. *Ecosystem Services*, 74(June), 101747. <https://doi.org/10.1016/j.ecoser.2025.101747>
- TEEB. (2010). *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. Earthscan.
- Tezel, A. Ç., Akpınar, A., Bor, A., & Alfredsen, K. T. (2025). Exploring Hydrological Response to Land Use/Land Cover Change Using the SWAT+ Model in the İznik Lake Watershed, Türkiye. *Water (Switzerland)*, 17(13).
<https://doi.org/10.3390/w17131924>
- Thiemann, M., Riebl, R., Haensel, M., Schmitt, T. M., Steinbauer, M. J., Landwehr, T., Fricke, U., Redlich, S., & Koellner, T. (2022). Perceptions of ecosystem services: Comparing socio-cultural and environmental influences. *PLOS ONE*, 17(10), e0276432.
- Tiessen, H., Feller, C., Sampaio, E. V. S. B., & Garin, P. (1998). Carbon Sequestration and Turnover in Semiarid Savannas and Dry Forest. *Climatic Change*, 40(1), 105–117.
<https://doi.org/10.1023/A:1005378305563>
- Topp, S. N., Pavelsky, T. M., Jensen, D., Simard, M., & Ross, M. R. V. (2020). Research

- trends in the use of remote sensing for inland water quality science: Moving towards multidisciplinary applications. *Water (Switzerland)*, 12(1), 1–34. <https://doi.org/10.3390/w12010169>
- Totino, M., Urdampilleta, C. M., Ithuralde, R. E., Giono, L. A., Cabrera, A. E., Lanzarotti, E., & Quintana, R. D. (2023). A methodological approach for the analysis of ecosystem services from the local communities' perspective. *Ambio*, 52(4), 786–801. <https://doi.org/10.1007/s13280-022-01807-y>
- Trabucco, A., & Zomer, R. J. (2022). *Global Aridity Index and Potential Evapotranspiration Database v3*. <https://doi.org/10.6084/m9.figshare.7504448.v5>
- Tran, M. D., Vantrepotte, V., Loisel, H., Oliveira, E. N., Tran, K. T., Jorge, D., Mériaux, X., & Paranhos, R. (2023). Band Ratios Combination for Estimating Chlorophyll-a from Sentinel-2 and Sentinel-3 in Coastal Waters. *Remote Sensing*, 15(6). <https://doi.org/10.3390/rs15061653>
- Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8(2), 127–150.
- Turnhout, E., Metze, T., Wyborn, C., Klenk, N., & Louder, E. (2020). The politics of co-production: participation, power, and transformation. *Current Opinion in Environmental Sustainability*, 42(2018), 15–21. <https://doi.org/10.1016/j.cosust.2019.11.009>
- U.S. Geological Survey. (2020). *Social Values for Ecosystem Services (SolVES)*. <https://code.usgs.gov/solves/solves-4.0/-/tree/release>
- United Nations. (2021). *System of Environmental-Economic Accounting— Ecosystem Accounting (SEEA EA)*. White cover publication, pre-edited text subject to official editing. 1–371. <https://seea.un.org/ecosystem-accounting>.
- Ustin, S. L., & Middleton, E. M. (2021). Current and near-term advances in Earth observation for ecological applications. *Ecological Processes*, 10(1), 1–57. <https://doi.org/10.1186/s13717-020-00255-4>
- Vagheei, H., & Boano, F. (2025). Freshwater riparian zones in a changing climate: A comprehensive review. *Ecological Indicators*, 176(February), 113600. <https://doi.org/10.1016/j.ecolind.2025.113600>
- Valenzuela, L., & del Valle Barrera, M. (2023). Beyond Ecological Economics and Development. In *Beyond Ecological Economics and Development*. Routledge. <https://doi.org/10.4324/9781003381143>
- Van Colen, W. R., Mosquera, P., Vanderstukken, M., Goiris, K., Carrasco, M. C., Decaestecker, E., Alonso, M., León-Tamariz, F., & Muylaert, K. (2017). Limnology and trophic status of glacial lakes in the tropical Andes (Cajas National Park, Ecuador). *Freshwater Biology*, 62(3), 458–473. <https://doi.org/10.1111/fwb.12878>
- Van Dieren, W. (Ed.). (1979). *Taking Nature into Account: A Report to the Club of Rome*. Springer.
- Van Rossum, G., & Drake, F. L. (2009). *Python 3 Reference Manual*. CreateSpace. <https://dl.acm.org/citation.cfm?id=1593511>
- Van Zanten, B. T., Verburg, P. H., Koetse, M. J., & Van Beukering, P. J. H. (2014). Preferences for European agrarian landscapes: A meta-analysis of case studies. *Landscape and Urban Planning*, 132, 89–101.

- <https://doi.org/10.1016/j.landurbplan.2014.08.012>
- Vanhellemont, Q. (2020). Sensitivity analysis of the dark spectrum fitting atmospheric correction for metre- and decametre-scale satellite imagery using autonomous hyperspectral radiometry. *Optics Express*, 28(20), 29948. <https://doi.org/10.1364/oe.397456>
- Vanhellemont, Q., & Ruddick, K. (2021). Atmospheric correction of Sentinel-3/OLCI data for mapping of suspended particulate matter and chlorophyll-a concentration in Belgian turbid coastal waters. *Remote Sensing of Environment*, 256(February), 112284. <https://doi.org/10.1016/j.rse.2021.112284>
- Vega, M., Pardo, R., Barrado, E., & Debán, L. (1998). Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. *Water Research*, 32(12), 3581–3592. [https://doi.org/10.1016/S0043-1354\(98\)00138-9](https://doi.org/10.1016/S0043-1354(98)00138-9)
- Venkateswarlu, T., & Anmala, J. (2024). Importance of land use factors in the prediction of water quality of the Upper Green River watershed, Kentucky, USA, using random forest. *Environment, Development and Sustainability*, 26(9), 23961–23984. <https://doi.org/10.1007/s10668-023-03630-1>
- Vermote, E., Roger, J. C., Franch, B., & Skakun, S. (2018). LASRC (Land Surface Reflectance Code): Overview, application and validation using MODIS, VIIRS, LANDSAT and Sentinel 2 data's. *International Geoscience and Remote Sensing Symposium (IGARSS)*, 2018-July(October 2020), 8173–8176. <https://doi.org/10.1109/IGARSS.2018.8517622>
- Villa, F., Bagstad, K. J., Voigt, B., Johnson, G. W., Portela, R., Honzák, M., & Batker, D. (2014). A methodology for adaptable and robust ecosystem services assessment. *PLoS ONE*, 9(3). <https://doi.org/10.1371/journal.pone.0091001>
- Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., & others. (2010). Global threats to human water security and river biodiversity. *Nature*, 467(7315), 555–561.
- Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social--ecological systems. *Ecology and Society*, 9(2).
- Walker, B., & Salt, D. (2006). *Walker and Salt. 2006. Resilience thinking.pdf*.
- Wang, A., Yang, D., & Tang, L. (2020). Spatiotemporal variation in nitrogen loads and their impacts on river water quality in the upper Yangtze River basin. *Journal of Hydrology*, 590. <https://doi.org/10.1016/j.jhydrol.2020.125487>
- Wang, L., Xu, M., Liu, Y., Liu, H., Beck, R., Reif, M., Emery, E., Young, J., & Wu, Q. (2020). Mapping freshwater chlorophyll-a concentrations at a regional scale integrating multi-sensor satellite observations with google earth engine. *Remote Sensing*, 12(20), 1–18. <https://doi.org/10.3390/rs12203278>
- Wang, Y., Liu, X., Wang, T., Zhang, X., Feng, Y., Yang, G., & Zhen, W. (2021). Relating land-use/land-cover patterns to water quality in watersheds based on the structural equation modeling. *Catena*, 206. <https://doi.org/10.1016/j.catena.2021.105566>
- Warren, M. A., Simis, S. G. H., Martinez-Vicente, V., Poser, K., Bresciani, M., Alikas, K., Spyarakos, E., Giardino, C., & Ansper, A. (2019). Assessment of atmospheric correction algorithms for the Sentinel-2A MultiSpectral Imager over coastal and inland waters. *Remote Sensing of Environment*, 225(September 2018), 267–289.

- <https://doi.org/10.1016/j.rse.2019.03.018>
- Wesström, I., Joel, A., & Messing, I. (2014). Controlled drainage and subirrigation - A water management option to reduce non-point source pollution from agricultural land. *Agriculture, Ecosystems and Environment*, 198, 74–82. <https://doi.org/10.1016/j.agee.2014.03.017>
- Westman, W. E. (1977). How Much Are Nature's Services Worth? *Science*, 197(4307), 960–964. <https://doi.org/10.1126/science.197.4307.960>
- Wetzel, R. G. (1983). *Limnology* (2nd ed.). Saunders College Publishing.
- Willcock, S., Martínez-López, J., Hooftman, D. A. P., Bagstad, K. J., Balbi, S., Marzo, A., Prato, C., Sciandrello, S., Signorello, G., Voigt, B., Villa, F., Bullock, J. M., & Athanasiadis, I. N. (2018). Machine learning for ecosystem services. *Ecosystem Services*, 33, 165–174. <https://doi.org/https://doi.org/10.1016/j.ecoser.2018.04.004>
- Williamson, C. E., Saros, J. E., & Schindler, D. W. (2009). Climate change: Sentinels of change. *Science*, 323(5916), 887–888. <https://doi.org/10.1126/science.1169443>
- Wilson, G., Aruliah, D. A., Brown, C. T., Chue Hong, N. P., Davis, M., Guy, R. T., Haddock, S. H. D., Huff, K. D., Mitchell, I. M., Plumbley, M. D., Waugh, B., White, E. P., & Wilson, P. (2014). Best Practices for Scientific Computing. *PLoS Biology*, 12(1). <https://doi.org/10.1371/journal.pbio.1001745>
- Wittmann, F., Householder, E., Lopes, A., de Oliveira Wittmann, A., Junk, W. J., & Piedade, M. T. F. (2015). Implementation of the Ramsar Convention on South American wetlands: an update. *Research and Reports in Biodiversity Studies*, 47. <https://doi.org/10.2147/rrbs.s64502>
- Wold, S., Sjöström, M., & Eriksson, L. (2001). PLS-regression: A basic tool of chemometrics. *Chemometrics and Intelligent Laboratory Systems*, 58(2), 109–130. [https://doi.org/10.1016/S0169-7439\(01\)00155-1](https://doi.org/10.1016/S0169-7439(01)00155-1)
- World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press.
- World Health Organization (WHO). (1998). *Guidelines for Drinking-water Quality* (2nd ed.). World Health Organization.
- Wu, J., & Lu, J. (2021). Spatial scale effects of landscape metrics on stream water quality and their seasonal changes. *Water Research*, 191. <https://doi.org/10.1016/j.watres.2021.116811>
- Wu, S., Liu, K. Di, Zhang, W., Dou, Y., Chen, Y., Zhang, T., & Li, D. (2024). An integrated analysis framework of supply, demand, flow, and use to better understand realized ecosystem services. *Ecosystem Services*, 69(July), 101649. <https://doi.org/10.1016/j.ecoser.2024.101649>
- Wyborn, C., Datta, A., Montana, J., Ryan, M., Leith, P., Chaffin, B., Miller, C., & Van Kerkhoff, L. (2019). Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annual Review of Environment and Resources*, 44, 319–346. <https://doi.org/10.1146/annurev-environ-101718-033103>
- Xia, K., Wu, T., Li, X., Wang, S., Tang, H., Zu, Y., & Yang, Y. (2024). A novel method for assessing water quality status using MODIS images: A case study of large lakes and reservoirs in China. *Journal of Hydrology*, 638(November 2023), 131545. <https://doi.org/10.1016/j.jhydrol.2024.131545>

- Xiong, J., Lin, C., Ma, R., & Cao, Z. (2019). Remote sensing estimation of lake total phosphorus concentration based on MODIS: A case study of Lake Hongze. *Remote Sensing*, 11(17), 1–19. <https://doi.org/10.3390/rs11172068>
- Xu, M., Liu, H., Beck, R., Lekki, J., Yang, B., Shu, S., Kang, E. L., Anderson, R., Johansen, R., Emery, E., Reif, M., & Benko, T. (2019). A spectral space partition guided ensemble method for retrieving chlorophyll-a concentration in inland waters from Sentinel-2A satellite imagery. *Journal of Great Lakes Research*, 45(3), 454–465. <https://doi.org/10.1016/j.jglr.2018.09.002>
- Xue, S., He, Y., Cai, H., Li, J., Zhu, L., & Ye, C. (2025). Risk assessment of non-point source pollution in tropical watersheds considering water functional zones. *Ecological Indicators*, 171(November 2024), 113128. <https://doi.org/10.1016/j.ecolind.2025.113128>
- Yang, L., Ziwen, Z., Lin, X., Hei, J., Wang, Y., & Zhang, A. (2025). AI-powered approaches for enhancing remote sensing-based water contamination detection in ecological systems. *Frontiers in Environmental Science*, 13(August), 1–15. <https://doi.org/10.3389/fenvs.2025.1612658>
- Yang, Z., Reiter, M., & Munyei, N. (2017). Estimation of chlorophyll-a concentrations in diverse water bodies using ratio-based NIR/Red indices. *Remote Sensing Applications: Society and Environment*, 6, 52–58. <https://doi.org/10.1016/j.rsase.2017.04.004>
- Yun, T., Li, J., Ma, L., Zhou, J., Wang, R., Eichhorn, M. P., & Zhang, H. (2024). Status, advancements and prospects of deep learning methods applied in forest studies. *International Journal of Applied Earth Observation and Geoinformation*, 131(May), 103938. <https://doi.org/10.1016/j.jag.2024.103938>
- Zagarese, H., Cravero, W., Villafañe, V., & Helbling, W. (1998). Efecto de la radiación ultravioleta sobre los ecosistemas acuáticos. *Ciencias Del Mar*, 8(45), 44–47.
- Zhang, F., Chen, Y., Wang, W., Jim, C. Y., Zhang, Z., Tan, M. L., Liu, C., Chan, N. W., Wang, D., Wang, Z., & Rahman, H. A. (2022). Impact of land-use/land-cover and landscape pattern on seasonal in-stream water quality in small watersheds. *Journal of Cleaner Production*, 357. <https://doi.org/10.1016/j.jclepro.2022.131907>
- Zhang, Q., & Justice, C. O. (2001). Carbon Emissions and Sequestration Potential of Central African Ecosystems. *AMBIO*, 30(6), 351–355.
- Zhang, Y., Kong, X., Deng, L., & Liu, Y. (2023). Monitor water quality through retrieving water quality parameters from hyperspectral images using graph convolution network with superposition of multi-point effect: A case study in Maozhou River. *Journal of Environmental Management*, 342(May), 118283. <https://doi.org/10.1016/j.jenvman.2023.118283>
- Zhang, Z., Huang, J., Duan, S., Huang, Y., Cai, J., & Bian, J. (2022). Use of interpretable machine learning to identify the factors influencing the nonlinear linkage between land use and river water quality in the Chesapeake Bay watershed. *Ecological Indicators*, 140(January), 108977. <https://doi.org/10.1016/j.ecolind.2022.108977>
- Zhang, Z., Zhang, F., Du, J., Chen, D., & Zhang, W. (2021). Impacts of land use at multiple buffer scales on seasonal water quality in a reticular river network area. *PLoS ONE*, 16(1 January). <https://doi.org/10.1371/journal.pone.0244606>

- Zhao, Q., Yu, L., Du, Z., Peng, D., Hao, P., Zhang, Y., & Gong, P. (2022). An Overview of the Applications of Earth Observation Satellite Data: Impacts and Future Trends. *Remote Sensing*, 14(8), 1–18. <https://doi.org/10.3390/rs14081863>
- Zhu, W., Yu, Q., Tian, Y. Q., Becker, B. L., Zheng, T., & Carrick, H. J. (2014). An assessment of remote sensing algorithms for colored dissolved organic matter in complex freshwater environments. *Remote Sensing of Environment*, 140(January), 766–778. <https://doi.org/10.1016/j.rse.2013.10.015>
- Zomer, R. J., Trabucco, A., Bossio, D. A., & Verchot, L. V. (2007). *Carbon, land and water: A global analysis of the hydrologic dimensions of climate change mitigation through afforestation/reforestation*.
- Zomer, R. J., Trabucco, A., Bossio, D. A., & Verchot, L. V. (2008). Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, Ecosystems & Environment*, 126, 67–80. <https://doi.org/10.1016/j.agee.2008.01.014>
- Zomer, R. J., Xu, J., & Trabucco, A. (2022). Version 3 of the Global Aridity Index and Potential Evapotranspiration Climate Database (Global-AI_PET_v3). *Scientific Data*, 9, 409. <https://doi.org/10.1038/s41597-022-01493-1>

Appended Papers

