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Review

Water resilience in the high Andean basins of Peru and Ecuador: A synthesis of hydrological modeling, cryosphere dynamics, and ecohydrological approaches under climate change (2011–2025)

Cristian Santiago Tapia Ramírez, Dennis Renato Manzano Vela*, Edmundo Danilo Guilcapi Pacheco, David Santiago León Armijos

Facultad de Recursos Naturales, Escuela Superior Politécnica de Chimborazo (ESPOCH), Riobamba 060150, Ecuador
*** Corresponding author:** Dennis Renato Manzano Vela, dennis.manzano@espoch.edu.ec

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Abstract: The high Andean basins of Peru and Ecuador supply freshwater to approximately 60% and 70% of their respective national populations. However, these systems are increasingly threatened by glacier retreat, land-use transformation, and climate variability, which jeopardize long-term water security. This study presents an integrative narrative review of 58 peer-reviewed scientific publications published between 2011 and 2025, focusing on hydrological modeling, cryospheric dynamics, hydrometeorological monitoring, climate change impacts, and ecohydrological processes in tropical Andean mountain systems. Following a systematic selection process, the reviewed evidence was organized into five thematic areas: advances in hydrological modeling under data-scarce conditions, validation of satellite precipitation products, glacio-hydrological and cryospheric dynamics, hydroclimatic scenario simulation, and ecohydrological approaches. The results reveal a sustained methodological transition from semi-distributed conceptual models (SWAT, HEC-HMS, and GR2M) toward physically based distributed models (MGB, PREVAH, and JULES), integrated with satellite products (GPM-IMERG, SM2RAIN, and ERA5-Land) and machine learning algorithms, significantly reducing the limitations associated with data scarcity. Climate projections under CMIP6 scenarios indicate increases of up to 60% in extreme precipitation intensity and up to 39% in annual runoff in some basins, while glacier mass loss could reduce dry-season water storage by as much as 25% over the coming decades. At the same time, land-use changes, including the conversion of páramo ecosystems to pasturelands and deforestation, have been shown to alter baseflow and infiltration processes independently of climatic forcing. The synthesis further reveals that water resilience in the Andes cannot be fully understood through physical hydrology alone. The conservation of water-regulating ecosystems such as páramos, bofedales, and montane forests plays a critical role in maintaining hydrological regulation and sustaining water availability under changing environmental conditions. The review highlights the importance of integrating hydrological processes, cryospheric dynamics, and ecosystem functions to improve water resilience assessments and support sustainable water resources management in the tropical Andes.

Keywords: water resilience; high Andean basins; hydrological modeling; cryospheric dynamics; páramo ecohydrology

1. Introduction

The high Andean basins of Peru and Ecuador are strategic hydrological systems for water security in the tropical Andes, supplying water for human consumption, agriculture, hydroelectric generation, and the maintenance of mountain ecosystems [1,2]. The hydrological dynamics of these basins are conditioned by pronounced

altitudinal gradients, steep topography, climatic heterogeneity, diversity of vegetation covers, storage processes associated with páramos, bofedales, organic soils, and glaciers. These hydrological systems face increasing pressures from deforestation, overgrazing, unplanned urbanization, and climate change, which threaten water availability, regulation, and quality for agricultural, energy, and domestic uses [3].

During recent decades, the retreat of tropical glaciers, estimated at approximately 40% of their extent since 1980, has modified the hydrological regimes of mountain basins, altering the seasonality of flows and the availability of water during the dry season [4–6]. This reduction in snow cover has occurred alongside greater interannual variability in precipitation, influenced by phenomena such as El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and the Intertropical Convergence Zone [7]. In the Ecuadorian case, an increase exceeding 1 °C in the mean temperature of inter-Andean basins has been reported between 1960 and 2010, along with variations in rainfall regimes of up to ±15% [8]. In this context, hydrological modeling has advanced from semi-distributed approaches with limited information, such as SWAT and HEC-HMS, toward physically-based distributed models such as MGB and PREVAH, capable of representing in greater detail the spatial heterogeneity of the terrain, vegetation cover, runoff generation, and storage mechanisms within the basin.

In parallel, the use of remote sensors and climatic products such as TRMM, GPM-IMERG, and SM2RAIN has partially compensated for the scarcity of rainfall data information in high Andean areas and strengthened the temporal analysis of hydrometeorological processes [9,10]. The integration of hydrological models, satellite data, and climate scenarios has allowed for the projection of relevant changes in regional water availability; for example, in Quito, an increase of 60% in the intensity of extreme rains has been estimated under the SSP5-8.5 scenario, while in the Guayas River basin, a 39% increase in annual runoff has been projected [11,12]. In contrast, studies in the binational Puyango-Tumbes basin have identified marked reductions in annual flow associated with land use change and the degradation of páramo and dry forest ecosystems [13]. These findings show that Andean water vulnerability does not depend solely on the climate, but also on the transformation of vegetation cover and territorial management [14,15]. Therefore, understanding water resilience in the Andes requires integrating physical, ecological, social, and institutional processes within sustainable water management frameworks [16–18]. Within this framework, this article analyzes research published between 2011 and 2025 on hydrological modeling, hydrometeorological monitoring, cryospheric dynamics, and integrated water resources management in the high Andean basins of Peru and Ecuador, with the purpose of identifying technical advances, information gaps, methodological synergies, and research perspectives aimed at strengthening the sustainable management of water resources.

2. Materials and methods

2.1. Methodological review design

The present study was developed through an integrative narrative review with a systematic orientation, focused on analyzing the evolution of hydrological and ecohydrological research in the high Andean basins of Peru and Ecuador between

2011 and 2025. The methodology was structured to identify methodological trends, technological advances, interdisciplinary approaches, and knowledge gaps related to water resilience in mountain ecosystems subjected to processes of climate variability and territorial transformation. The review integrated research oriented toward hydrological modeling, hydrometeorological monitoring, glacio-hydrological dynamics, evaluation of satellite products, simulation of climate scenarios, and socio-hydrological approaches associated with integrated water resources management.

The methodological structure was organized into three main components: i) bibliographic collection and selection, ii) systematization and validation of scientific information, and iii) comparative analysis and integrative interpretation of results. This approach allowed for the articulation of hydrological, climatic, ecological, and socio-institutional perspectives under a framework of water sustainability applied to tropical Andean ecosystems

2.2. Geographical scope of the review

The geographical scope of this review encompasses high Andean basins located in Peru and Ecuador, including hydrological systems associated with both the Pacific and Amazonian drainage slopes. The reviewed studies cover different mountain catchments and hydrological environments characterized by marked altitudinal gradients, climatic heterogeneity, and contrasting vegetation and land-cover conditions. The spatial distribution of the study locations identified in the reviewed literature is presented in **Figures 1** and **2**, which illustrate the geographical coverage of the analyzed studies in Ecuador and Peru, respectively.

2.3. Information sources and search strategy

The bibliographic collection was carried out between May and December 2025 using internationally recognized indexed scientific databases, including Scopus, Web of Science, SciELO, and Google Scholar. Priority was given to publications with a verifiable DOI, university institutional affiliation, and a direct relationship with research developed in tropical Andean regions of Peru and Ecuador. The analysis concentrated particularly on three thematic axes: i) multi-source integration for Andean hydrometeorological modeling, ii) impacts of climate change and the cryosphere on water availability, and iii) ecohydrological and socio-institutional approaches applied to sustainable water management.

The search strategy was structured using Boolean equations aimed at retrieving scientific literature related to Andean hydrological dynamics, hydrometeorological modeling, and integrated assessment of mountain basins. Technical terms in English were used due to their predominance in high-impact international publications, also incorporating conceptual synonyms and truncations to expand terminological coverage and reduce retrieval biases. Queries were executed primarily in Scopus and Web of Science, restricting the search to the title, abstract, and keyword fields.

The general search equation integrated terms associated with Andean basins, hydrological models, climate variability, cryosphere, satellite precipitation, and water resources, including models widely used in the region such as SWAT, MGB, PREVAH, and JULES. Additionally, terms related to ecohydrology, socio-hydrology,

ecosystem services, and integrated water resource management were incorporated for the purpose of identifying emerging interdisciplinary research linked to sustainability and water resilience in high Andean ecosystems.

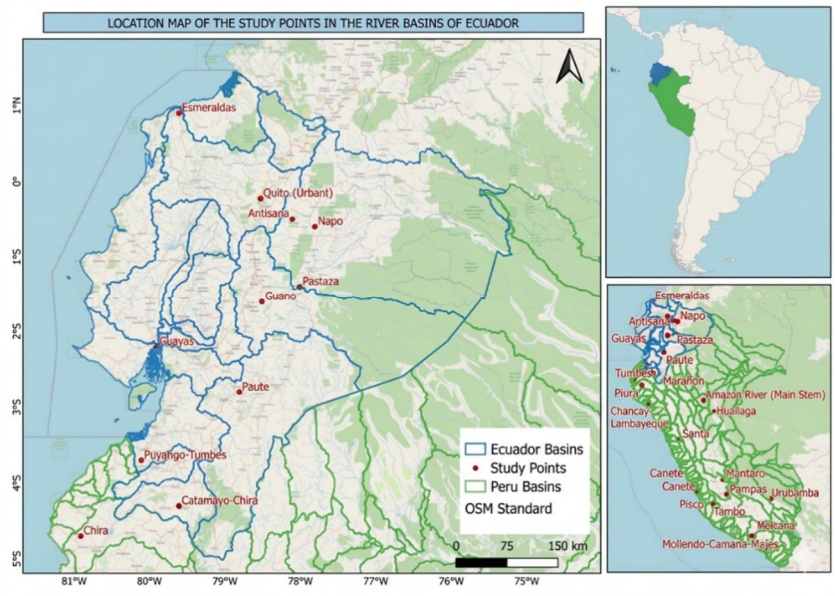


Figure 1. Location of the study points in the basins of Ecuador.

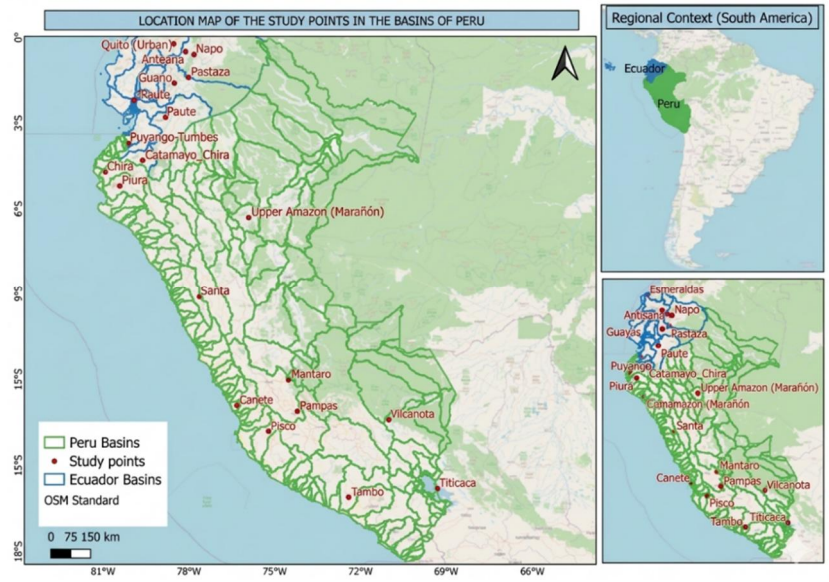


Figure 2. Location of the study points in the basins of Peru.

2.4. Inclusion and exclusion criteria

The inclusion criteria considered scientific publications developed between 2011 and 2025, review articles, and institutional technical documents from specialized agencies such as the National Institute of Meteorology and Hydrology of Ecuador (INAMHI), the National Service of Meteorology and Hydrology of Peru (SENAMHI), and the National Institute for Research in Glaciers and Mountain Ecosystems (INAIGEM). Only research published in English, with a DOI or academic URL available, and directly related to hydrological modeling, precipitation analysis, water

balance, cryosphere, climate simulation, or water resources management in tropical Andean basins was selected.

On the other hand, publications without peer review, exclusively theoretical studies without regional application, non-validated gray literature, research outside the Andean geographical context, and documents without access to the full text or without verifiable methodological support were excluded. This procedure allowed for maintaining thematic consistency and academic rigor within the analyzed bibliographic corpus.

2.5. Selection and systematization procedure

The analysis procedure was developed in three consecutive phases. In the first stage, 150 potentially relevant documents were identified through automated searches and manual review of cross-references. Subsequently, an evaluation for thematic and methodological relevance was performed, eliminating redundant studies, publications without full access, or research that did not meet the established criteria. Finally, the selected documents were organized using descriptive synthesis matrices that included information regarding authorship, year of publication, DOI, country of study, basin analyzed, type of hydrological model, temporal scale, and main purpose of the research.

The thematic systematization allowed for classifying the studies into categories associated with the validation of satellite data and climate reanalysis, glacio-hydrological processes, hydroclimatic scenarios, and ecohydrological and socio-hydrological approaches. For bibliographic organization and thematic coding, Excel matrices and reference managers such as Mendeley and Zotero were used, facilitating the comparative integration of results between research developed at different spatial and temporal scales.

To improve methodological transparency and clarify the study selection process, a PRISMA-style flow diagram was incorporated to summarize the identification, screening, eligibility assessment, and final inclusion of the scientific documents considered in the review corpus, show in **Figure 3**. This diagram provides a visual representation of the transition from the initial records identified in scientific databases and cross-reference searches to the final set of 58 studies included in the integrative and comparative analysis.

Although the core review corpus was restricted to scientific publications developed between 2011 and 2025, a limited number of supplementary references published outside this temporal window were also cited selectively. These additional sources were not counted among the 58 studies included in the main analytical corpus; rather, they were incorporated to strengthen specific theoretical, methodological, and contextual arguments. Their use was limited to supporting conceptual discussion, methodological clarification, and interpretation of emerging trends, without altering the temporal scope or the quantitative structure of the reviewed evidence.

2.6. Information validation and comparative analysis

The validation of the information was carried out through theoretical triangulation and contrast of results with research indexed in Scopus and Web of

Science. A cross-review was conducted aimed at verifying conceptual coherence, methodological timeliness, and thematic consistency among the selected studies, reducing possible duplications and interpretive biases. As a result of the purification and critical evaluation process, 58 research papers were finally selected for integrative and comparative analysis.

The final comparative analysis focused on identifying predominant methodological trends, scientific innovations, persistent limitations, and emerging perspectives within contemporary Andean hydrology. For each study, information was extracted related to spatial and temporal scales, climatic products used, validation metrics, modeling structures, operational limitations, and main hydrological results. Likewise, a critical review of the conceptual framework of high Andean hydrology was developed, considering the interaction between physical, ecological, and social processes, as well as the increasing incorporation of satellite data, hybrid approaches, and socioeconomic variables within regional hydrological modeling. This approach allowed for the construction of an integrative vision of the current state of knowledge on water resilience and sustainable water management in the high Andean basins of Peru and Ecuador.

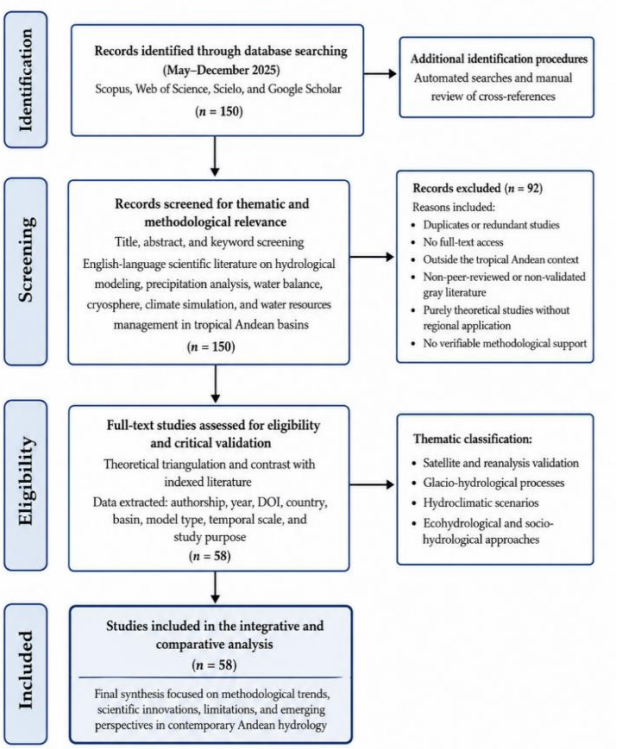


Figure 3. PRISMA-style flow diagram of the literature search and study selection process.

3. Results and discussion

3.1. Characterization of the reviewed scientific evidence

Out of the total of 150 scientific documents identified during the bibliographic search and screening stage, 58 studies met the inclusion criteria defined in the methodology. The selected works were organized according to their authorship,

geographical context, thematic focus, type of modeling used, and availability of a verifiable DOI or academic URL. Appendix **Table A1** synthesizes this evidence and presents a representative overview of the recent evolution of hydrological research developed in the high Andean basins of Ecuador and Peru during the 2021–2025 period.

The integrative analysis highlights a progressive transition from conceptual hydrological approaches with limited data availability toward distributed modeling schemes that incorporate remote sensing, climate reanalysis, energy balances, and socio-ecological variables. This methodological evolution is shown in **Figure 4** and responds both to the advancement of computational and satellite tools and to the need to understand, with greater spatial and temporal resolution, the combined effects of climate change, glacier retreat, and land-use transformations on mountain ecosystems strategic for regional water security. In this context, recent research shows a steady increase in the use of integrated models capable of simultaneously representing hydrological processes, cryospheric dynamics, and water demand scenarios associated with agricultural, urban, hydroelectric, and industrial activities.

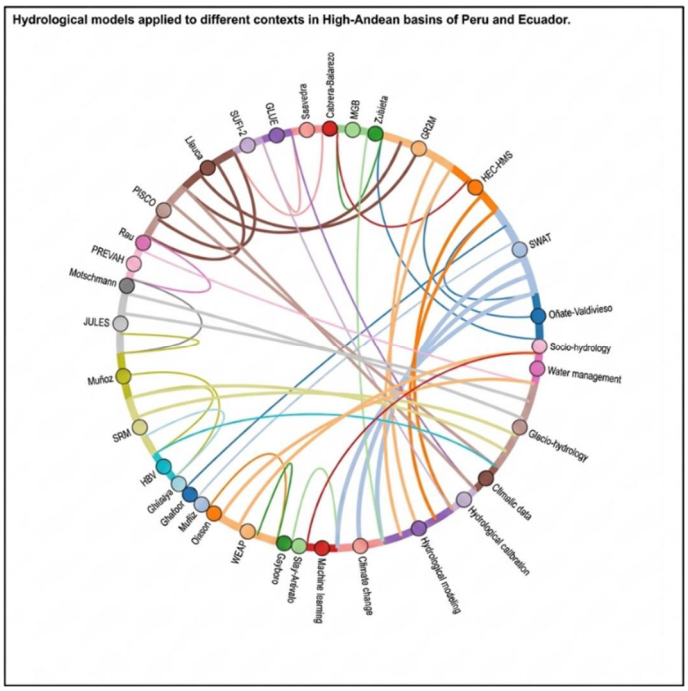


Figure 4. Hydrological models applied to various contexts in high Andean basins of Peru and Ecuador.

The geographical distribution of the reviewed studies shows a predominance of research developed in basins of the Amazonian and Andean Pacific slopes, including strategic hydrological systems such as Vilcanota, Santa, Guayas, Cata mayo-Chira, Titicaca, Maranon, Pastaza, and Napo. Likewise, an increasing articulation between national research and Ecuador–Peru binational studies are observed, particularly in shared basins subject to similar climatic and anthropic pressures. From a thematic perspective, the analyzed literature reflects a progressive consolidation of interdisciplinary approaches where physical hydrology is integrated with ecohydrological, socio-hydrological, and water governance components, evidencing a

conceptual transition from analyses focused exclusively on runoff processes toward approaches oriented toward water resilience and territorial sustainability.

Regarding the modeling tools used, the reviewed studies show a marked predominance of semi-distributed and distributed hydrological models. The SWAT (Soil and Water Assessment Tool) model constitutes the most widely used tool within the analyzed literature, due to its ability to represent the combined effects of climate, vegetation cover, agricultural management, and soil characteristics on the water balance and sediment production at the basin scale. Complementarily, distributed models such as MGB and PREVAH have been widely used to represent runoff generation and propagation processes in high Andean and Amazonian systems characterized by high spatial heterogeneity. PREVAH, in particular, has shown high applicability in glacio-hydrological simulations and energy balances in mountain basins.

On the other hand, the JULES (Joint UK Land Environment Simulator) model has been incorporated mainly in research oriented toward the study of cryospheric processes, atmosphere-surface interaction, and simulation of energy, water, and carbon flows in páramo ecosystems and glacier regions. In contrast, semi-distributed conceptual tools such as HEC-HMS continue to be used in precipitation–runoff simulations and hydrological analysis of extreme events in basins with limited availability of observational information. Models with simplified structures such as GR2M maintain relevance in hydrological regionalization studies and monthly water balance simulations due to their low parameterization requirements. Additionally, WEAP (Water Evaluation and Planning System) has been used mainly in research oriented toward water planning and integrated assessment of water supply and demand, while SRM (Snowmelt Runoff Model) has been applied specifically in studies related to melt dynamics and glacier contribution to baseflow.

The frequency analysis shown in **Figure 5** shows that 26% of the reviewed studies employed SWAT for general hydrological simulations, evaluation of land-use changes, and analysis of climate scenarios in basins of Peru, Ecuador, and binational systems. The MGB model represented 19% of the identified applications, mainly in Amazonian basins and large-scale high Andean systems such as Santa, Titicaca, Napo, Pastaza, and Maranon. PREVAH and JULES individually reached a frequency of 14%, concentrating on glacio-hydrological simulations, energy balances, and evaluation of glacier retreat in systems such as Vilcanota, Antisana, and Santa. Furthermore, HEC-HMS represented 10% of the reviewed research, while GR2M participated in 9 % of the studies related to hydrological regionalization and monthly flow simulation. Finally, WEAP and SRM presented frequencies of 5% and 3%, respectively, focusing mainly on integrated water management scenarios and modeling of snow and glacier processes.

The quantitative and qualitative characterization of the reviewed scientific evidence allowed for the structuring of the results analysis into five interrelated thematic axes: i) advances in hydrological modeling under conditions of data scarcity, ii) hydrological validation of satellite products and reanalysis data, iii) glacio-hydrological and cryospheric modeling, iv) hydroclimatic simulation under climate change scenarios, and v) ecohydrological and socio-hydrological approaches applied to sustainable water resource management. These axes reflect the recent evolution of

Andean hydrology toward multi-scale and interdisciplinary approaches aimed at understanding the complex interaction between climatic processes, mountain ecosystems, and socio-environmental dynamics in contexts of increasing water vulnerability.

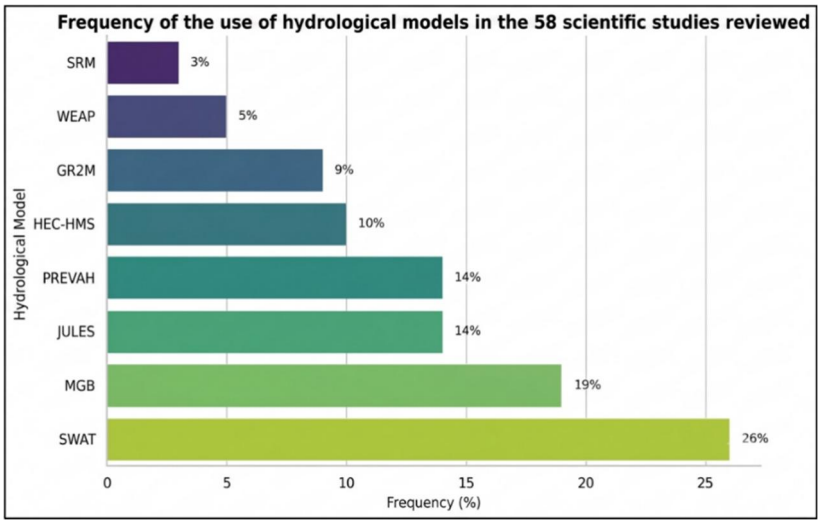


Figure 5. Frequency of the use of hydrological models.

3.2. Hydrological modeling in high Andean basins with limited data availability

Hydrological modeling in the high Andean basins of Peru and Ecuador has developed in a context marked by low density of meteorological and hydrometric stations, discontinuity in time series, and high physiographic heterogeneity of mountain systems. In this scenario, early systematic efforts primarily resorted to conceptual and semi-distributed models, such as SWAT, HEC-HMS, and GR2M, due to their ability to represent precipitation-runoff processes, soil storage, and basin-scale hydrological response with moderate information requirements.

Physically based land-surface models such as JULES have also been evaluated in humid tropical Andes-Amazon environments, highlighting both their potential and the challenges associated with representing hydrological processes under data-scarce conditions [19]. Furthermore, the parameterization of JULES for different land-cover types in the tropical Andes has extended its application to high Andean ecosystems such as páramos and punas, improving the representation of land-surface processes under contrasting vegetation and environmental conditions [20].

The application of SWAT in the binational Cata mayo-Chira basin demonstrated that a parameterization based on slope, soil texture, vegetation cover, altitude, and hydrological response units can generate acceptable performances even under conditions of low rainfall density, with Nash-Sutcliffe efficiency values exceeding 0.70 [21]. This type of approach was relevant for the Andean region, as it allowed for progress in the hydrological representation of extensive basins where direct observation remains insufficient [22].

SWAT-based strategies specifically designed for data-scarce regions of Peru have likewise sought to optimize model implementation where hydrometeorological information is limited [16].

In addition, distributed models such as TETIS have been implemented using pedotransfer functions to estimate soil hydraulic properties and artificial neural networks to reconstruct incomplete hydroclimatic series, providing an alternative for hydrological simulation in data-scarce high Andean basins [23].

The subsequent incorporation of distributed models expanded the capacity for spatial analysis and allowed for a more detailed representation of the internal variability of high Andean basins. Zubieta et al. [24] implemented the MGB model in Amazonian sub-basins of Peru through parameter regionalization and the use of satellite observations, which improved the calibration of flow generation and propagation processes. Their results indicated that the delimitation of hydrologically homogeneous zones can reduce the average simulation bias by more than 20% in basins with limited information. In Ecuador, studies such as those of [25] showed the applicability of HEC-HMS in páramo environments, where the hydrological response is strongly conditioned by the dominance of subsurface flow, the high retention capacity of organic soils, and the persistence of baseflow. HEC-HMS has also been applied in experimental areas of the Guayas River basin to simulate runoff production under agricultural conditions, illustrating its applicability across contrasting Ecuadorian hydrological environments [26]. These results suggest that model selection should not depend solely on structural complexity, but on its correspondence with the dominant processes of each hydrological system.

The most recent methodological advances have focused on automatic parameterization, multi-objective calibration, and explicit uncertainty evaluation. Multi-objective model-selection frameworks have further been proposed to constrain structural uncertainty and improve the robustness of hydrological climate-impact assessments [27]. The application of methods such as GLUE and SUFI-2 has allowed for the analysis of parametric sensitivity, the reduction of structural uncertainty, and the simultaneous optimization of various performance metrics in distributed and semi-distributed models [28,29]. In parallel, the GR2M model has remained useful in monthly flow simulations due to its parsimonious structure and low data requirements [30,31], particularly in coastal and high Andean basins without continuous records [14]. At the national scale, PISCO_HyM_GR2M has extended this parsimonious approach by providing a monthly water-balance framework for Peru based on GR2M [32]. The integration of products such as PISCO HyM, meteorological station data, ERA5-Land reanalysis, and satellite observations has contributed to expanding the spatial and temporal coverage of hydrological simulations in Peru and Ecuador [33]. In southern Ecuador, high-resolution radar observations combined with meteorological station data have also been used to improve river-discharge simulation in high Andean catchments [34].

The combination of hydrological modeling and satellite precipitation has also been evaluated in sparsely observed basins of the eastern Central Andes, providing additional alternatives for areas with limited ground data [35].

Overall, the reviewed evidence shows a transition from models dependent on limited local information toward multi-source approaches that combine regionalization, remote sensing, and advanced calibration to represent altitudinal gradients, climatic contrasts, and cover differences characteristic of the tropical Andes.

3.3. Hydrological validation of satellite products and reanalysis data

The validation of satellite precipitation products and reanalysis data constitutes one of the most relevant lines of research for recent high Andean hydrology, due to the persistent scarcity of in situ observations and the operational difficulty of maintaining hydrometeorological networks in mountain areas. Products such as TRMM, GPM-IMERG, SM2RAIN, and ERA5-Land have been incorporated into hydrological studies to extend temporal records, improve the spatial characterization of precipitation, and analyze extreme events in difficult-to-access basins [36–38]. However, their performance varies depending on altitude, vegetation cover, orographic exposure, and the temporal structure of rain events, thus their application requires local validation and bias correction processes.

Accordingly, the adjustment of global precipitation datasets using regional information has been proposed as a strategy to improve hydrological simulations in tropical Andean watersheds [39].

Zulkafli et al. [40] compared satellite products with observations in Andes-Amazon transition zones and evidenced that relative errors tend to change with altitude and precipitation seasonality. Their results showed that products such as IMERG and TRMM can adequately represent seasonal rain dynamics, although they present limitations in capturing intense or highly localized events. Hydrological evaluation of GPM-IMERG in the Peruvian-Ecuadorian Amazon Basin has likewise demonstrated its usefulness as an alternative precipitation input in regions with sparse gauge networks [41].

Satgé et al. [42] evaluated different versions of GPM-IMERG and SM2RAIN with meteorological stations in southern Peru, identifying that bias correction and integration with local measurements improve the performance of hydrological simulations. These findings highlight that satellite products should not be treated as direct substitutes for ground stations, but as complementary inputs within multi-source integration schemes. Near-real-time satellite precipitation products have also been evaluated for sub-daily flood simulations in sparsely gauged Peruvian Andean watersheds, highlighting their potential for operational applications while emphasizing the importance of local performance assessment [43].

On the Peruvian Pacific slope, Satgé et al. [42] reported that the combination of SM2RAIN and ERA5-Land improved the estimation of simulated flows by approximately 15% compared to configurations based solely on conventional records. In this line, Fernandez-Palomino et al. [44] developed RAIN4PE as a regional daily precipitation product for basins in Peru and Ecuador, integrating more than 400 meteorological stations with satellite observations using machine learning techniques. Its spatial resolution of 0.05° represents a significant advance for regional hydrometeorological modeling and for the analysis of climate trends in high Andean areas. Complementarily, bottom-up satellite precipitation products have been assessed on the Peruvian Pacific slope for river-streamflow estimation, further emphasizing the need for basin-specific hydrological validation [45].

The reviewed evidence indicates that the integration of satellite products, ground stations, and reanalysis data has improved hydrological simulation capacity in areas with low observational density. At the national scale, ensemble-based flood

forecasting systems such as GloFAS have also been evaluated in Peru as an alternative for anticipating flood events where conventional monitoring is limited [46].

However, limitations persist in the representation of precipitation variability and in the performance of satellite precipitation products under complex regional conditions. Therefore, these products require basin-specific validation, uncertainty assessment, and, where necessary, bias-correction strategies based on local observations [42].

3.4. Glacio-hydrological modeling and cryospheric dynamics

Tropical glaciers in Peru and Ecuador, generally located between 4800 and 6700 m a.s.l., fulfill a regulatory function in high Andean hydrological systems, especially during the dry season, when meltwater can sustain a considerable fraction of baseflow. The reviewed literature agrees that glacier retreat observed since the 1980s has significantly reduced ice storage and modified flow seasonality in melt-dependent basins [18]. This reduction in cryospheric volume has direct implications for rural communities, agricultural systems, hydroelectric infrastructure, and cities that depend on the regulatory contribution of mountain basins.

At a broader regional scale, Rau et al. [47] analyzed hydroclimatic changes across Peruvian Pacific drainage catchments using the Budyko-Zhang framework, showing that water-resource variability differs markedly among basins according to their climatic and hydrological characteristics. These findings indicate that changes in water availability cannot be attributed exclusively to glacier retreat, but must also be interpreted in relation to precipitation variability, evapotranspiration, and the specific hydroclimatic characteristics of each basin.

Glacio-hydrological modeling has therefore become an important tool for understanding how changes in cryospheric processes affect runoff generation and seasonal water availability. In Ecuador, Olsson et al. [12] compared different levels of structural complexity in glacio-hydrological models applied to the Antisana basin, including SRM, HBV, and JULES. Their results show that physically based models can more consistently represent melt processes under climate change scenarios, although they require a higher density of meteorological, glaciological, and energy data. In Peru, Calizaya et al. [48] applied the SRM model in the Santa River sub-basin to represent snow and glacier melt under different climate scenarios. Together, these studies show that the choice between parsimonious and physically detailed models must consider data availability, the study objective, and the temporal scale of analysis [49].

In terms of water management, glacio-hydrological modeling reveals a progressive decrease in the natural regulation capacity of tropical glaciers. Although meltwater can represent up to 40% of total flow during the dry season in certain Andean basins, this contribution will tend to decrease as the remaining glacier mass diminishes [18]. In the Santa River basin, the contribution of glacier meltwater has also been evaluated in relation to environmental flow requirements during drought events, highlighting the importance of cryospheric water sources for maintaining downstream environmental flows under water-scarcity conditions [50]. Studies integrating glacierized water supply with socioeconomic water demand further

demonstrate that future water security depends on both cryospheric change and the evolution of human water requirements [51]. Therefore, future research should integrate glacier monitoring, hydrological modeling, environmental flow requirements, water demand, and adaptation scenarios to anticipate changes in the water security of territories dependent on cryospheric sources.

3.5. Hydroclimatic modeling and climate change scenarios

The integration between climate and hydrological models has allowed for the evaluation of future impacts of climate variability and global warming on water availability in the tropical Andes. These approaches combine climate projections, global or regional circulation models, emission scenarios, and basin hydrological models to analyze changes in precipitation, temperature, evapotranspiration, surface runoff, extreme flows, and water deficits [52].

Daily-scale hydrological modeling in the Peruvian Andes has similarly demonstrated the value of coupling climate projections with basin models to evaluate future changes in water resources [53].

Climate change assessments in the Lake Titicaca Basin have also shown that projected hydroclimatic changes affect meteorological, hydrological, and agricultural droughts differently. Using the GR2M model at a monthly scale, [13] analyzed these contrasting drought responses, highlighting the need to distinguish among drought types when evaluating future water vulnerability in the Andean Altiplano [13].

In Quito, Núñez Mejía et al. [54] employed 19 CMIP6 models to project changes in hydrometeorological extremes and estimated increases of up to 60% in the intensity of short-duration rains and 50% in peak flows toward the end of the 21st century. These results are especially relevant for Andean urban areas where territorial growth, soil sealing, and the occupation of risk zones increase employed SWAT in the Puyango-Tumbes binational se exposure to flash floods.

Beyond Quito, climate-model projections have also been applied to rainfall prediction in the Machángara tropical Andean basin, reinforcing the use of future climate scenarios for local water-resource assessment in Ecuador [55].

In the Guayas basin, located in a transition zone between the Andes and the Ecuadorian coastal plain, Ghafoor et al. [56] applied SWAT forced with CMIP6 projections under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, reporting increases of up to 39% in surface runoff and reductions in soil water storage. These results suggest that an increase in effective precipitation does not necessarily imply an improvement in useful water availability, due to possible changes in infiltration, soil storage, erosion, and flash flood generation. In parallel, Murillo et al. [33] employed SWAT in the Puyango-Tumbes binational basin and noted that the combination of land-use changes and climate variability could reduce annual flows by 26% by 2050. Similar SWAT applications in Ecuador-Peru binational basins have confirmed the importance of explicitly representing LULC dynamics when assessing changes in hydrological response [57]. This difference between basins evidences that hydroclimatic impacts are not spatially uniform and depend on the interaction between climate, vegetation cover, soils, slope, and anthropic pressure.

In the Peruvian Amazon, Paiva et al. [58] estimated that deforestation in

approximately 12% of the basin could increase runoff by 38%, confirming that cover transformations can equal or even exceed the direct effects of climate change on the hydrological response. This evidence reinforces the need to simultaneously analyze climate scenarios and land-use changes, as both processes modify the partition of precipitation between infiltration, evapotranspiration, storage, and runoff. Studies employing integrated water planning models, such as WEAP, have allowed for the incorporation of supply, demand, use efficiency, and water allocation rules within future scenarios [59]. Overall, these works estimate that, without adaptation strategies, deficits during the dry season could increase by up to 30% in sectors of the central Andean region.

The accumulated evidence indicates that climate change does not act in isolation, but in interaction with territorial processes such as agricultural expansion, deforestation, urbanization, páramo degradation, and pressure on surface and groundwater sources [13]. Therefore, hydroclimatic modeling in high Andean basins must advance toward schemes that integrate climate scenarios, land-use trajectories, and multisectoral water demand. This orientation is particularly relevant for water sustainability studies, as it allows physical resource simulation to be linked with water allocation, planning, and adaptation strategies [59].

3.6. Ecohydrological and socio-hydrological approaches for sustainable water management

Recent literature on high Andean basins shows an expansion of the traditional hydrological approach toward ecohydrological and socio-hydrological perspectives. This transition responds to the recognition that water availability does not depend solely on precipitation, temperature, or runoff, but also on the conservation status of regulatory ecosystems, land-use patterns, and forms of water governance. Modeling of Andean páramo ecosystems has further shown that environmental and population changes can modify hydrological regulation and therefore need to be incorporated into water-management scenarios [60].

In this sense, páramos, bofedales, high Andean wetlands, and montane forests act as functional units for the storage, regulation, and gradual release of water, especially during dry periods [61–63]. Evidence from forested tropical Andean catchments further demonstrates the importance of montane ecosystems in controlling seasonal and annual water balances [61].

Ross et al. [63] analyzed, using Sentinel-2 imagery and hydrological monitoring, the seasonal storage and release dynamics of water in bofedales of the central Altiplano. Their results show that these wetlands function as natural reservoirs that retain water during the wet season and release it progressively during the dry season, contributing to baseflow regulation. Monge-Salazar et al. [64] compared natural and artificial bofedales, identifying that drainage, overgrazing, and vegetation alteration decrease water retention capacity and modify groundwater flows. These results confirm that the degradation of high Andean ecosystems can directly affect the hydrological stability of basins, even when climate conditions remain relatively constant.

From a socio-hydrological perspective, [17] developed a baseline for Integrated

Water Resources Management in basins of southern Ecuador, incorporating governance indicators alongside hydrological simulations. This type of approach allows for linking the physical response of the basin with institutional, regulatory, and community aspects that influence water distribution and use [65] on the other hand, applied machine learning algorithms to complete missing flow series in the Guayas River basin, reaching NSE values of 0.98, evidencing the potential of data methods to improve the continuity of hydrological records in tropical basins. In contrast, Matovelle [66] demonstrated that the conversion of páramo to pasture increases pollution and reduces baseflows, showing the sensitivity of these ecosystems to cover changes.

Modeling applied to planning has also incorporated decision criteria linked to infrastructure, energy, and territorial development. Orozco et al. [67] estimated hydroelectric potential in regions with data scarcity using GIS and MATLAB tools, evidencing that hydrological modeling can support energy investment processes when integrated with spatial analysis and water availability assessment. However, these approaches need to be complemented with environmental and social criteria, particularly in high Andean basins where water regulation depends on sensitive ecosystems and communities that maintain direct relationships with the territory.

Overall, the reviewed ecohydrological and socio-hydrological studies show that sustainable water management in the Andes requires integrating three analytical dimensions: the physical dynamics of the basin, the ecological functionality of regulatory ecosystems, and the institutional capacity to guide decisions on use, conservation, and adaptation [68,69]. This integration is consistent with a systemic view of sustainability, in which water resilience depends as much on the precision of models as on the conservation of ecological processes and the effective participation of territorial actors.

3.7. Critical synthesis, methodological limitations, and future research directions

The literature review demonstrates that when comparing the hydrological behavior of different basins under climate change conditions, responses vary significantly from one Andean watershed to another. These differences are associated with the diverse processes that dominate each unique hydrological system. Such is the case of the Santa and Vilcanota basins, which are characterized by the presence of Andean glaciers, where streamflow is largely regulated by seasonal snow and ice melt. Consequently, these basins are highly vulnerable to climate change due to increasing temperatures and the resulting glacier retreat [47,48]. In contrast, basins dominated by páramo ecosystems, such as those found in Ecuador, exhibit a greater capacity for hydrological regulation because of the substantial water storage provided by their organic soils. This contributes to the maintenance of baseflow and partially mitigates the impacts of climate change, at least in the short term [62,70].

Another important source of variability is related to differences in land cover and ecosystem conservation status.

Regional evidence from tropical Andean headwater catchments has shown that land-use and land-cover conditions exert a strong control on hydrological response,

particularly through changes in runoff generation and water regulation [71].

Studies conducted in the Madre de Dios River Basin in the Peruvian Amazon using the SWAT hydrological model, as well as in the Rircay River sub-basin in Azuay Province, Ecuador, have shown that deforestation and land-use changes associated with agricultural expansion increase surface runoff and streamflow by significantly altering infiltration and evapotranspiration processes [58,66]. Consistent with these findings, the application of multiple SWAT model variants in tropical Andean catchments has further demonstrated that land-use and land-cover changes can substantially modify streamflow response, reinforcing the importance of explicitly representing vegetation-cover dynamics in hydrological simulations [72].

Consequently, hydrological responses should not be explained solely by changes in precipitation and temperature, but also by the effects these changes exert on watershed processes. This is evidenced by projections developed for the binational Puyango–Tumbes Basin, where erosion and sediment production were found to be more sensitive to climatic and vegetation-cover changes than streamflow itself [33].

Most of this research has been conducted using hydrological modeling, a field that has experienced significant advances over the last decade. Nevertheless, important limitations remain, particularly the scarcity of continuous hydrometeorological records in high-mountain and remote regions. This limitation affects model calibration and validation processes by increasing the uncertainty of hydrological simulations, even when distributed models and satellite products are employed [42]. Likewise, regionalization techniques that seek to transfer calibrated parameters from gauged basins to ungauged watersheds based on physical and climatic similarity criteria are also susceptible to introducing uncertainty into the resulting simulations [15]. Comparative analyses of regionalization methods in ungauged basins further emphasize that model transferability depends strongly on hydrological similarity and regional heterogeneity [73].

More recent studies reveal a gradual transition toward integrative approaches that combine hydrology with ecosystem services and social dimensions. Research examining hydrological processes alongside socioeconomic systems and water governance demonstrates that water resilience depends not only on water availability but also on institutional capacity, adaptive management, and ecosystem conservation. Furthermore, the outputs generated by hydrological simulation models require the participation of local communities and decision-makers to ensure their acceptance and practical implementation [74]. This perspective is particularly relevant in the tropical Andes, where local populations depend directly on the water-regulation services provided by páramos, bofedales, and montane forests. The conceptual analysis of these statements is shown in the **Figure 6**.

Ultimately, future research should focus on strengthening interdisciplinary approaches capable of integrating climate change, land-use dynamics, ecosystem processes, and social and institutional factors within a common modeling framework. Advances in machine learning techniques, including Random Forest, Artificial Neural Networks, Ensemble Kalman Filters (EnKF), and Particle Filters (PF), together with data assimilation methods and high-resolution precipitation products such as RAIN4PE, offer promising opportunities to reduce uncertainty and improve hydrological predictions in data-scarce regions. However, the increasing adoption of

these approaches also introduces important methodological challenges. Machine learning algorithms rely primarily on complex statistical relationships derived from historical observations and may therefore fail to adequately represent the underlying hydrological processes governing mountain catchments. When trained on limited datasets, these models may be particularly susceptible to overfitting, resulting in reduced predictive performance when applied under conditions different from those used during calibration [75,76]. Their reliability is especially uncertain under future climate change scenarios, where non-stationary conditions, unprecedented extreme events, and progressive changes in glaciers and ecosystems may invalidate the historical statistical relationships used for model training [14,76]. Furthermore, the limited interpretability of some machine-learning techniques hinders the identification of causal mechanisms and reduces their usefulness for long-term water resources planning [14,75,77]. To overcome these limitations, it is necessary to develop hydrological modeling frameworks that integrate data-driven approaches with physically based models, thereby improving both predictive performance and scientific understanding of high Andean watersheds. Considering all these factors, such developments are essential for strengthening water resilience assessments and supporting the sustainable management of water resources in the high Andean basins of Peru and Ecuador, which are increasingly vulnerable to floods and droughts [14,44].

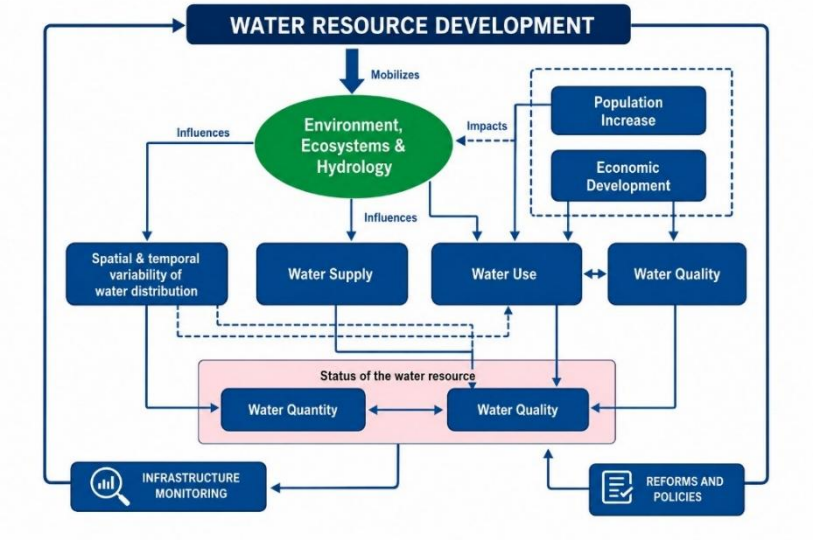


Figure 6. Conceptual framework linking climate change, regulatory ecosystems, governance, and water resilience in high Andean basins of Peru and Ecuador.

4. Conclusion

The reviewed evidence demonstrates that hydrological research in the high Andean basins of Peru and Ecuador has advanced toward more integrated modeling schemes, capable of responding to the limited availability of meteorological and hydrometric records. The incorporation of satellite products, reanalysis data, and regionalization techniques has expanded the spatial and temporal coverage of simulations, especially in difficult-to-access areas. In this context, products such as IMERG, ERA5-Land, and RAIN4PE are consolidating as high-value inputs to represent precipitation, estimate flows, and analyze hydroclimatic variability in

mountain systems with low observational density.

Multi-objective calibration approaches, uncertainty analysis, and hybrid modeling with machine learning have modified the way hydrological model performance is evaluated in the Andean region. The emphasis is no longer limited to obtaining a single flow prediction, but to estimating response ranges, reducing parametric biases, and improving the interpretation of hydrological processes under conditions of climate variability. Methods such as SUFI-2, GLUE, and machine learning algorithms offer methodological alternatives to complete missing series, improve the prediction of extreme events, and strengthen the evaluation of future scenarios in basins with incomplete information.

The results also evidence that high Andean water availability depends on the interaction between climate change, glacier retreat, land-use transformation, and the degradation of regulatory ecosystems. The loss of glacier cover, deforestation, wetland drainage, overgrazing, and the conversion of páramos to pastures alter infiltration, soil storage, surface runoff, and baseflow persistence. Therefore, the conservation and restoration of páramos, bofedales, and montane forests must be considered a priority strategy to sustain water regulation, reduce vulnerability during the dry season, and improve the adaptive capacity of basins facing environmental change scenarios.

At the same time, water resilience in the Andes of Peru and Ecuador requires moving beyond exclusively hydrological approaches and incorporating social, institutional, and governance variables within models and planning processes. Sustainable water management demands shared databases, binational monitoring networks, common validation protocols, and scientific training programs between both countries. This cooperation would allow for the consolidation of an applied Andean hydrology, oriented toward generating local knowledge, supporting territorial management decisions, and strengthening the water security of communities, cities, agricultural systems, and energy sectors dependent on mountain basins.

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Appendix

Table A1. Literature analysis (n = 58).

No.	Reference.	Study title	Country	Study area	Model/scale	Purpose
1	Zubieta et al. [13]	Comparative analysis of climate change impacts on meteorological, hydrological, and agricultural droughts in the Lake Titicaca Basin.	Peru / Bolivia	Lake Titicaca Basin	GR2M / Monthly	Analyze the impact of climate change on different types of droughts in the Altiplano.
2	Llauca et al. [14]	Constraining flood forecasting uncertainties through streamflow data assimilation in the tropical Andes of Peru: Case of the Vilcanota River Basin.	Peru	Vilcanota River Basin	Data assimilation / Daily	Reduce uncertainty in flood forecasts through data assimilation.
3	Asurza-Véliz et al. [15]	Regional parameter estimation of the SWAT model: Methodology and application to river basins in the Peruvian Pacific drainage.	Peru	Pacific slope	SWAT / Daily	Estimate daily flow series through parameter regionalization.
4	Daneshvar et al. [16]	Development of Strategy for SWAT Hydrologic Modeling in Data-Scarce Regions of Peru.	Peru	Quilca-Chili River Basin	SWAT / Daily	Develop modeling strategies in data-scarce regions.
5	Mera-Parra et al. [17]	Establishment of the baseline for the IWRM in the Ecuadorian Andean basins: Land use change, water recharge, meteorological forecast and hydrological modeling.	Ecuador	Catamayo and Chira	SWAT / Monthly	Establish a baseline for IWRM evaluating land use changes.
6	Zulkafli et al. [19]	A critical assessment of the JULES land surface model hydrology for humid tropical environments.	Peru	Humid tropical Andes-Amazon Mountain basin	JULES-LSM / Daily	Evaluate the representation of hydrological flows in global surface models in data-scarce environments.
7	Chou et al. [20]	Parameterizing the JULES land surface model for different land covers in the tropical Andes.	Regional	Páramos and Punas	JULES / Hourly / Daily	Parameterize the JULES model for high Andean ecosystems.
8	Oñate-Valdivieso and, Sendra [21]	Semidistributed Hydrological Model with Scarce Information: Application to a Large South American Binational Basin.	Ecuador & Peru	Catamayo-Chira binational basin	SWAT / (Daily)	Implement SWAT in a basin with low density of meteorological stations and scarce data.
9	Hurtado-Pidal et al. [22]	Flood hazard assessment in data-scarce watersheds using model coupling, event sampling, and survey data.	Ecuador	Tena River Basin	HEC-HMS and HEC-RAS / Event	Evaluate flash flood hazards by coupling models.
10	Patiño Velasco et al. [23]	Distributed Hydrological Modeling of a High Andean Basin Using Pedotransfer Functions and Incomplete Data Series.	Peru & Bolivia	Lake Titicaca Region	GR4J and snow model / (Daily)	Evaluate spatial-temporal consistency of 12 satellite precipitation products.

Table A1. (*Continued*).

No.	Reference.	Study title	Country	Study area	Model/scale	Purpose
11	Zubieta et al. [24]	Impacts of satellite-based precipitation datasets on rainfall-runoff modeling of the Western Amazon basin of Peru and Ecuador.	Peru & Ecuador	Western Amazon Basin	MGB-IPH / (Daily)	Evaluate impacts of satellite precipitation datasets (TMPA, CMORPH, PERSIANN) on modeling.
12	Cabrera-Balarezo et al. [25]	Evaluation of the HEC-HMS model for the hydrological simulation of a paramo basin.	Ecuador	Páramo basin	HEC-HMS / Daily	Evaluate HEC-HMS performance in páramo ecosystems.
13	Marcillo and Toulkeridis [26]	Hydrological modeling for the discharge production in an experimental area of the Guayas river basin, Ecuador.	Ecuador	Baba River	HEC-HMS / Event / Daily	Simulate direct runoff production in an experimental agricultural area.
14	Saavedra et al. [27]	A multi-objective approach to select hydrological models and constrain structural uncertainties for climate impact assessments.	Various	Andean and global basins	Multiple (HBV, GR4J) / Daily	Propose a multi-objective model selection framework for climate assessments.
15	Carlos Mendoza et al. [28]	Calibration and uncertainty analysis for modelling runoff in the Tambo River Basin, Peru, using Sequential Uncertainty Fitting Ver-2 (SUFI-2) Algorithm.	Peru	Tambo River Basin	SWAT / Daily / Monthly	Calibrate and analyze the uncertainty of the SWAT model in an arid zone basin.
16	Fernandez-Palomino et al. [29]	Towards a more consistent eco-hydrological modelling through multi-objective calibration: A case study in the Andean Vilcanota River basin, Peru.	Peru	Vilcanota River Basin	SWAT / Daily / Monthly	Improve the consistency of the eco-hydrological model through multi-objective calibration.
17	Lavado Casimiro et al. [30]	Assessment of climate change impacts on the hydrology of the Peruvian Amazon–Andes basin.	Peru	Peruvian Amazon-Andes basins (Ucayali, Huallaga, Marañón)	GR2M, MWB3 / Monthly	Investigate changes in hydrological response due to changes in precipitation and evapotranspiration (IPCC).
18	Rau et al. [31]	Assessing multidecadal runoff (1970–2010) using regional hydrological modelling under data and water scarcity conditions in Peruvian Pacific catchments.	Peru	45 Peruvian Pacific Basins	GR1A and GR2M / (Monthly & Annual)	Estimate surface water availability under natural conditions (1970–2010).
19	Llauca et al. [32]	PISCO_HyM_GR2M: A Model of Monthly Water Balance in Peru (1981–2020)	Peru	National Scale	GR2M / Monthly	Develop and validate a monthly water balance model for the entire Peruvian territory.
20	Murillo et al. [33]	Effect del LULC sobre la respuesta hidrológica en la cuenca Puyango-Tumbes, Ecuador-Perú	Ecuador and Peru	Puyango-Tumbes	SWAT / Daily / Annual	Simulate the impact of land use scenarios on the water balance.
21	Mejía-Veintimilla et al. [34]	River discharge simulation in the high Andes of southern Ecuador using high-resolution radar observations and meteorological station data.	Ecuador	Tomebamba and Yanuncay	CEQUEAU / Hourly / Daily	Simulate flows using high-resolution radar observations.

Table A1. (*Continued*).

No.	Reference.	Study title	Country	Study area	Model/scale	Purpose
22	Baltazar et al. [35]	Hydrological modeling in a region with sparsely observed data in the eastern Central Andes of Peru, Amazon.	Peru	Chicllarazo River Basin	SWAT + IMERG / Daily / Monthly	Evaluate applicability of IMERG satellite precipitation data.
23	Strauch et al. [39]	Adjustment of global precipitation data for enhanced hydrologic modeling of tropical Andean watersheds	Various	Andean sub-basins of the Upper Amazon Basin	SWAT, ISI-MIP2 Ensembles / (N/A)	Propose ways to adjust global precipitation data (WFDEI) to improve modeling.
24	Zulkafli et al. [40]	Projected increases in the annual flood pulse of the Western Amazon	Peru, Ecuador & Colombia	Western Amazonia	Tethys-Chloris (T&C) / (Daily)	Evaluate projected changes in the flood pulse due to climate change.
25	Zubieta et al. [41]	Hydrological modeling of the Peruvian-Ecuadorian Amazon Basin using GPM–IMERG satellite-based precipitation dataset.	Peru & Ecuador	Peruvian-Ecuadorian Amazon Basin	MGB-IPH / (Daily)	Evaluate the performance of GPM-IMERG satellite precipitation in hydrological modeling.
26	Satgé et al. [42]	Reliability of SM2RAIN precipitation datasets in comparison to gauge observations and hydrological modelling over arid regions.	Various	Arid regions	GR4J / (Daily)	Evaluate the reliability of SM2RAIN-based precipitation data.
27	Llauca et al. [43]	Assessing near real-time satellite precipitation products for flood simulations at sub-daily scales in a sparsely gauged watershed in Peruvian Andes.	Peru	Piura River Basin	GR4H / Hourly	Evaluate real-time satellite products for flood simulation at sub-daily scales.
28	Fernandez-Palomino et al. [44]	A novel high-resolution gridded precipitation dataset for Peruvian and Ecuadorian watersheds—development and hydrological evaluation.	Peru / Ecuador	RAIN4PE	Random Forest / Daily	Develop a new hydrologically corrected precipitation dataset (RAIN4PE).
29	Qquenta et al. [45]	Assessment of bottom-up satellite precipitation products on river streamflow estimations in the Peruvian Pacific Drainage.	Peru	Pacific slope	Hydrological models / Daily / Monthly	Evaluate satellite data for estimating flows in coastal rivers.
30	Bischiniotis et al. [46]	Evaluation of a global ensemble flood prediction system in Peru	Peru	Entire Peruvian territory	GloFAS / (Daily)	Evaluate the capacity of the GloFAS system to predict floods in Peru.
31	Rau et al. [47]	Hydroclimatic change disparity of Peruvian Pacific drainage catchments	Peru	Peruvian Pacific basins	Budyko-Zhang framework / (Annual)	Analyze the variability of water resources and their relationship with climate.
32	Calizaya et al. [48]	Modelling snowmelt runoff from tropical Andean glaciers under climate change scenarios in the Santa River sub-basin (Peru).	Peru	Santa River Sub-basin	SRM / Daily	Model the contribution of snow and glacier melt under different climate scenarios.

Table A1. (*Continued*).

No.	Reference.	Study title	Country	Study area	Model/scale	Purpose
33	Muñoz et al. [49]	Comparing model complexity for glacio-hydrological simulation in the data-scarce Peruvian Andes	Peru	Vilcanota-Urubamba Basin	SHAMAN / Daily	Evaluate if parsimonious models can outperform complex models in data-scarce basins.
34	Motschmann et al. [51]	Current and future water balance for coupled human-natural systems – Insights from a glacierized catchment in Peru	Peru, Bolivia, Ecuador, Colombia	Tropical Andes	Glacier mass balance / (Monthly/Annual)	Quantify the contribution of glacial melt to water use.
35	van Soesbergen and Mulligan [52]	Potential outcomes of multi-variable climate change on water resources in the Santa Basin, Peru.	Peru	Santa River Basin	WaterWorld / (Monthly)	Model the impact of changes in precipitation and temperature on the water balance.
36	Andres et al. [53]	Water resources and climate change impact modelling on a daily time scale in the Peruvian Andes	Peru	Peruvian Andes (Vilcanota)	PREVAH, GCMs (CSMK3, BCM2) / (Daily)	Model climate change impacts on water resources at a daily scale.
37	Núñez Mejía et al.[54]	Climate change impacts on hydrometeorological and river hydrological extremes in Quito, Ecuador	Ecuador	Quito City	Conceptual/Statistical / Daily	Investigate climate change impacts on extremes.
38	Vázquez-Patiño et al. [55]	The Assessment of Rainfall Prediction Using Climate Models Results and Projections under Future Scenarios: The Machángara Tropical Andean Basin Case.	Ecuador	Machángara Basin (Chanlud and El Labrado stations)	Random Forest + climate-model projections / Monthly rainfall	Evaluate rainfall prediction using climate-model outputs and project rainfall under RCP 4.5 and RCP 8.5 scenarios.
39	Ghafoor et al. [56]	Model-based analysis of the impact of climate change on hydrology in the Guayas River basin (Ecuador).	Ecuador	Guayas River Basin	SWAT / Monthly	Investigate climate change impact on hydrological regime.
40	Murillo et al. [57]	Use of the SWAT model to simulate the hydrological response to Lulc in a Binational Basin between Ecuador and Peru.	Ecuador / Peru	Catamayo-Chira	SWAT / Daily	Implement a model in a basin with low density of stations.
41	Paiva et al. [58]	Hydrological response assessment of Land Cover Change in a Peruvian Amazonian Basin Impacted by deforestation using the SWAT Model.	Peru	Huallaga River Basin	SWAT / Daily / Monthly	Evaluate impact of deforestation on Amazonian hydrological response.
42	Goyburo et al. [59]	Assessment of present and future water security under anthropogenic and climate changes using WEAP model in the Vilcanota-Urubamba Catchment, Cusco, Perú.	Peru	Vilcanota-Urubamba Basin	WEAP / Monthly	Evaluate current and future water security under climate change.
43	Flores-López et al. [60]	Modeling of Andean Páramo Ecosystems' Hydrological Response to Environmental Change	Peru	Quiroz-Chipillico Basin, Piura	WEAP / (Monthly/Scenarios)	Simulate impacts of environmental and population changes in páramo ecosystems.

Table A1. (*Continued*).

No.	Reference.	Study title	Country	Study area	Model/scale	Purpose
44	Clark et al. [61]	The hydrological regime of a forested tropical Andean catchment	Peru	Kosñipata Basin	Isotopic mixing model, PT-JPL / (Daily / Annual)	Quantify seasonal and annual water balances in montane cloud forests.
45	Correa et al. [62]	A concerted research effort to advance the hydrological understanding of tropical páramos	Regional	Páramo Ecosystems	Review (iMHEA) / (Various)	Synthesize current knowledge and propose a research agenda for páramo hydrology.
46	Ross et al. [63]	Seasonal water storage and release dynamics of bofedal wetlands in the Central Andes	Peru	Vilcanota Mountains	In situ monitoring / Hourly / Daily	Quantify seasonal water storage and release capacity in wetlands.
47	Monge-Salazar et al. [64]	Ecohydrology and ecosystem services of a natural and an artificial bofedal wetland in the central Andes	Peru	Central Andes	Water balance / Seasonal	Compare ecosystem services between natural and artificial wetlands.
48	Stay-Arevalo et al. [65]	Estimating missing daily streamflow data in a tropical basin with pronounced seasonal variability: A comparative case study from the Guayas River Basin, Ecuador.	Ecuador	Guayas River Basin	Random Forest / Daily	Compare models for estimating missing daily flow data.
49	Matovelle [66]	Páramo to Pasture Conversion in a Mountain Watershed: Effects on water quality and quantity	Ecuador	Rircay River	Non-linear / Historical	Evaluate the effect of converting páramo to pastures.
50	Orozco et al. [67]	Methodology for Hydroelectric Potential Evaluation in High Jungle Area with Scarce Topographic and Hydrological Information Using GIS and Algorithm MATLAB	Peru	Utcubamba Basin	GIS + MATLAB / Monthly	Evaluate hydroelectric potential in high jungle areas.
51	Jarrin-Perez et al. [70]	Hydrologic simulation of a neotropical alpine catchment influenced by conductive topsoils in the Ecuadorian Andes.	Ecuador	Machángara River Basin	SWAT-HS / Daily	Simulate the hydrology of páramo ecosystems with conductive soils.
52	Ochoa-Tocachi et al. [71]	Impacts of land use on the hydrological response of tropical Andean catchments	Peru, Ecuador & Bolivia	25 headwater basins in the tropical Andes	Participatory monitoring / (N / A)	Analyze the impact of land use and land cover on the regional hydrological response.
53	Valencia et al. [72]	Streamflow response to land use/land cover change in the tropical Andes using multiple SWAT model variants	Colombia	Chico River watershed, Colombian Andes	SWAT, SWAT-T, and SWAT-Tb / Daily	Evaluate the influence of land-use change, land cover, and different representations of the Leaf Area Index (LAI) on streamflow response, using multiple variants of the SWAT model.
54	Arsenault et al. [73]	Streamflow prediction in ungauged basins: Analysis of regionalization methods in a hydrologically heterogeneous region of Mexico	Mexico / Regional	30 hydrologically heterogeneous catchments in Mexico	GR4J, HMETS and MOHYSE / Daily	Evaluate and compare regionalization methods (multiple linear regression, spatial proximity, and physical similarity) for streamflow prediction in ungauged basins.

Table A1. (*Continued*).

No.	Reference.	Study title	Country	Study area	Model/scale	Purpose
55	Brauman KA, et al. [74]	Producing valuable information from hydrologic models of nature-based solutions for water	Global	Multiple cases	InVEST / Monthly / Annual	Analyze how models inform the efficacy of Nature-based Solutions.
56	Farfán et al. [75]	A hybrid neural network-based technique to improve the flow forecasting of physical and data-driven models: Methodology and case studies in Andean watersheds	Ecuador	Machángara Alto and Chulco rivers, Paute Basin	WEAP, GR2M, ANN and hybrid ANN / Monthly	Improve streamflow forecasting by combining physical and data-driven hydrological models through a hybrid ANN-based technique.
57	Llauca et al. [76]	Construction of a daily streamflow dataset for Peru using a similarity-based regionalization approach and a hybrid hydrological modeling framework.	Peru	National Scale	ARNO/VIC + RAPID / Daily	Develop a national model to generate daily flow series.
58	Duque-Sarango et al. [77]	Evaluation of the Hydrological Modeling System HEC-HMS for the Hydrological Simulation of a Tropical Andean Micro-basin	Ecuador	Chaquilcay River micro-basin, Azuay	HEC-HMS / Event	Simulate rainfall-runoff response and estimate peak flows for different return periods in a data-scarce tropical Andean micro-basin.