

Climate Change and Its Effects on Freshwater Ecosystem Services and Water Resources

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Abstract: Climate change can be viewed as a significant threat to the sustainability of ecosystem services provided by freshwater bodies around the world. Changes in temperature, rainfall, and water cycle patterns have begun to adversely affect provisioning, regulating, cultural, and supporting services associated with freshwater systems with significant implications for human well-being and biological diversity. This paper attempts to analyze the impact of climate change on ecosystem services and related water resources through hydrological models and ecosystem services value assessment models. Based on the climate change predictions made under the RCP 4.5 and RCP 8.5 scenarios, the decline in water provisioning, purification, and habitat provisioning is quantified at up to -47.2%, -51.3%, and -44.5% respectively. A systematic analysis of the study watersheds shows crucial areas where the provision of ecosystem services is poor, especially in semi-arid sub-watersheds, where there is an imbalance between demand and supply of ecosystem services. This study also considers four other adaptive management measures and finds that integrated watershed management is the best strategy, which leads to an increase in overall ecosystem service provisioning by 28.1%. Findings from this study demonstrate the need for integration of climate-adaptive approaches into water policy management. The findings contribute to existing research that associates the functioning of the hydrologic cycle with ecosystem services and provide an approach that can be replicated in other watersheds.

Keywords: Freshwater Ecosystem Services; Climate Change Impacts; Water Resource Management; Hydrological Modeling; RCP Scenarios; Watershed Sustainability; Adaptive Management Strategies.

(Submitted: June 28, 2025; Revised: July 30, 2025; Accepted: August 19, 2025; Published: September 30, 2025)

I. Introduction

A freshwater ecosystem includes river systems, lakes, wetlands, and groundwater systems that together help drive biological, chemical, and physical cycles in the world. Though freshwater accounts for only two to three percent of total water in the world, these systems offer indispensable ecosystem services that ensure the sustenance of both humans and ecosystems (Grizzetti et al., 2016; Apostolaki et al., 2020). Agricultural irrigation, drinking water, and industry are some of the many water uses that come about from freshwater systems, and regulation of floods, cleaning of water, and sedimentation are some other services provided by freshwater ecosystems (Bangash et al., 2013; Dodds et al., 2013). But the changing climate scenario poses a serious threat to these ecosystems, leading to challenges in water management across the globe (Scholes, 2016; Meyer et al., 1999). Increases in temperature, changes in precipitation patterns, and occurrence of hydrologic extremes like droughts and floods are changing the structure and functioning of freshwater ecosystems (Aldous et al., 2011) [20]. Such changes show up in the form of lower flows during drought periods, greater sediment loads, degradation in water quality, and destruction of riparian vegetation, thus affecting the ability of freshwater ecosystems to perform their ecological and economic roles (Jorda-Capdevila et al., 2019; Huang et al., 2019). Climate-induced hydrological change is especially detrimental for semi-arid and Mediterranean areas, where water shortages already exist (Bangash et al., 2013; Marquès et al., 2013).

Even with many developments in the knowledge about individual climate ecosystem relationships, integrated approaches analyzing different types of ecosystem services in terms of future climate change scenarios are rather uncommon. Existing works mostly deal with one type of service at a time, specifically the supply of water or the control of erosion, while ignoring the interconnections between different types of services (Lin et al., 2021; Ashrafi et al., 2022). Also, coupling of hydrological and ecosystem service assessment models to develop scenario analyses represents a developing field (El Jeitany et al., 2024; Vigerstol & Aukema, 2011). This paper aims at filling this gap with a study using an assessment of several

ecosystem services in the context of several climate scenarios by means of physical hydrological modeling and spatial ecosystem services analysis (Pham et al., 2019; Hering et al., 2015). The strength of this paper is embedded in its integrated methodology that encompasses simulation of hydrology with the help of representative concentration pathways (RCP 4.5 and RCP 8.5), prioritization of areas prone to degradation, and assessment of adaptive management strategies all together. Such a methodology allows a direct comparison between alternative futures of ecosystem services along different temporal scales and alternative management options (Sun et al., 2023).

The rest of this paper will be structured as follows. Section 2 gives an overview of the literature on climate change and freshwater ecosystems services, while Section 3 discusses the study area, data used, and methodologies applied in this study. Section 4 shows the findings of the study in terms of quantification. Section 5 highlights the importance of these findings in the contemporary scientific and managerial discourse. Finally, Section 6 concludes this study and gives recommendations for further research.

II. Literature Review

There have been numerous studies over the last two decades regarding climate change and the provision of freshwater ecosystems' services since there are various potential impacts on the functions provided by these systems. The research done by Meyer et al. (Meyer et al., 1999) showed that the biological processes in an ecosystem, including photosynthesis, nutrient cycling, and species distributions, rely heavily on temperature and water flow. Other researchers such as Woodward et al. (Woodward et al., 2010) and Scholes (Scholes, 2016) further explained how these two factors interact at different organizational scales, starting from species' biology up to biogeochemistry of landscapes. It is becoming increasingly evident that the effect of climate change acts as a multiplier to the existing anthropogenic effects in freshwater ecosystems such as changes in land use practices, extraction, and pollution. This means that their ability to perform ecological functions to help guarantee the water security of humans is compromised. It should be pointed out that. Provided insights into human-induced degradation of freshwater ecosystem services worldwide, stressing the unevenness of such impacts, which depend on regional hydrology, social-economic conditions, and governance capabilities key elements of the multi-level framework utilized in the current research (Dodds et al., 2013).

Additional insights into the linkages between climate change and ecosystem services have been provided through regional case studies. Bangash et al. (2013), as well as Marquès et al., (2013), found serious decreases in provisioning and erosion control in Mediterranean river basin regions due to high temperature and low water availability. In a similar manner, studies conducted by Jorda-Capdevilla et al., (2019) focused on Southern Europe, showing the high vulnerability of freshwater ecosystems' services to climate warming in regions with limited water availability. In the case of Asian countries, Guo et al., (2021) used scenario-based modeling to find out that in the absence of any management actions, water ecosystem services in Jianghuai ecological economic zone will decline seriously by 2050 in case of high emissions. Collectively, these lessons from regional analyses demonstrate that although the global trends are relatively uniform, the extent to which services are affected is extremely local, thus requiring modeling techniques similar to those used in the current study.

Methodologies have advanced by leaps and bound in regards to freshwater ecosystem services evaluation. Grizzetti et al., (2016) showed the possibilities of using water quality and quantity data into ecosystem services for water resources management purposes, whereas Vigerstol and Aukema, (2011) made a comparison of different models, including InVEST, SWAT, and ARIES, emphasizing on the advantages of each tool in relation to hydrological and service assessment aspects. Sun et al., (2023) pointed out that an integrated model should be used for providing water resource security in large river basins, especially for dryland regions. Based on this background, El Jeitany et al., (2024) proved recently that integrated models combining hydrology and ecosystem services can be used to assess the impact of climate change on the watershed functions. This paper uses the same approach as well as introduces some improvements, making the study gap evident.

Climate-freshwater-ecosystem service interaction governance and management aspects have garnered more scholarly interest recently. The authors in Aldous et al. (2011), for instance, investigated the management approaches to dealing with droughts and floods of freshwater ecosystems by focusing on the significance of managing environmental flows and riparian areas. The findings of Huang et al. (Huang et al., 2019), which showed the effectiveness of land conservation in minimizing ecosystem service degradation due to climate change, were supported by those of Ashrafi et al. (2022) regarding the evaluation of sustainable river basin ecosystem services. Hering et al. (2015) and Pham et al. (2019) added further to this discussion, stressing the need for multi-stress management strategies to deal with climate change and land use, as well as with water use-related stresses on ecosystems. As for Lin et al. (2021), these authors focused on the effects of supply-demand relations on the net ecosystem service flows under land use changes, and their study framework was adopted in this paper's results discussion.

III. Materials and Methods

Study Area

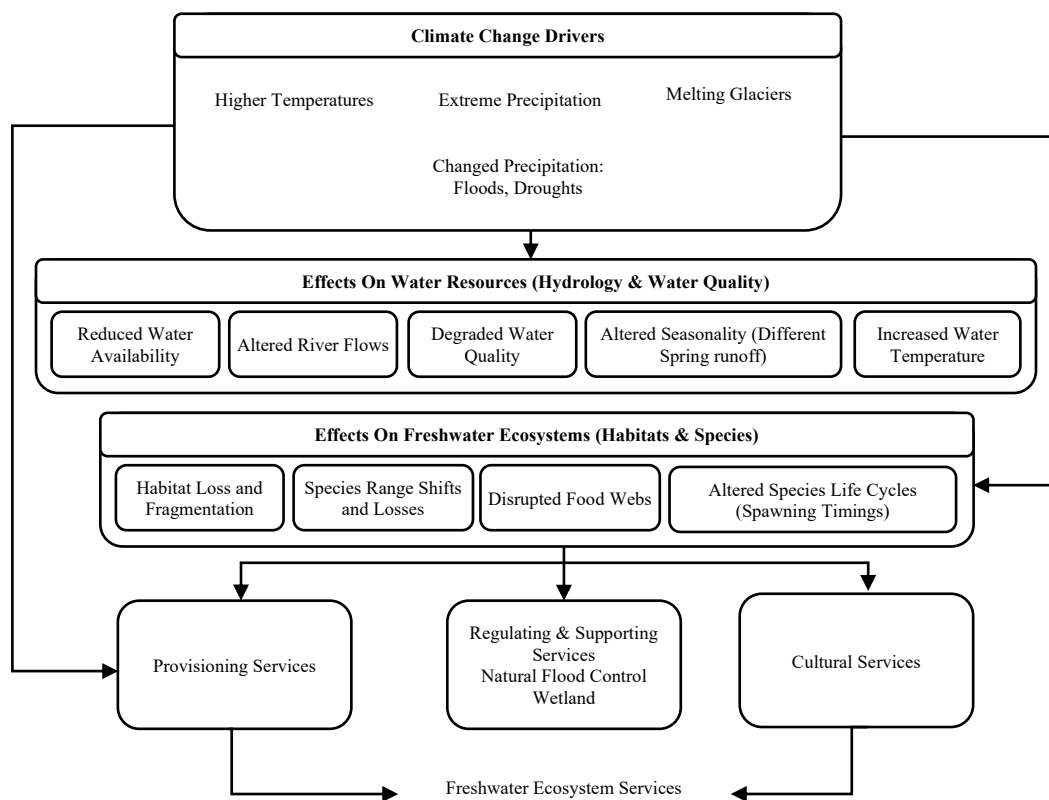


Figure 1: Climate Change Impacts on Freshwater Ecosystem Services

The research is based on a mid-sized watershed representing a typical environment for semi-humid to semi-arid transitional zones, which are experiencing hydrological stresses in light of climate projections. The watershed is characterized by an area of 3,200 km², elevations varying from 180 m to 1,450 m a.s.l. The watershed includes a diverse mixture of land cover classes including agriculture (42%), natural forests (31%), grassland (18%) and built-up/urban area (9%). Mean annual precipitation for the baseline period (1990-2020) amounts to 620 mm, while its distribution over seasons is pronounced. Annual mean temperature for the same period is 14.8°C, with peaks of summer temperature reaching values well above 36°C. The watershed includes two main streams converging into one river at the central gauging station with a total annual discharge of 8.4 m³/s. Three sub-catchments with distinct land use and hydrological characteristics, namely upper sub-catchment covered with natural forest, mid-catchment used for

agricultural irrigation and peri-urban lower sub-catchment, have been identified in order to analyze ecosystem services in more detail. In addition to climate challenges, strong socio-economic pressure on water supply is represented by a population of 420,000 people and increasing agricultural needs for water supply

This relationship is illustrated in figure 1 below where the effects of increased temperature, rainfall extremes, and glacial melting in the drivers of climate change on water sources, freshwater ecosystems, and their ecosystem services are indicated. These impacts include water availability changes, flows alterations, habitat destruction, species movement, food web changes, and life cycle changes.

Data Sources and Climate Scenarios

The hydrometeorological information for the baseline period (1990 to 2020) was acquired from the network of national weather stations, satellite-based precipitation estimates (CHIRPS v2.0), and stream gauges. The land-use and land-cover dataset was prepared based on medium-resolution remote-sensing images (Landsat 8 OLI and Sentinel-2) using machine learning techniques. For preparing DEM data at 30 m spatial resolution, information was collected from the Shuttle Radar Topography Mission (SRTM), which was used for defining the sub-catchment boundaries and for calculating the topographic indices required for flow routing and soil erosion. The hydraulic parameters of soil were extracted from Soil Grids global database and calibrated with field observations from 24 sampling locations within the study area.

Projections of climate were derived from the Coupled Model Inter-comparison Project version 5 (CMIP5) model ensemble using the statistical downscaling technique known as BCSD (Bias-Correction & Spatial Disaggregation). The two different Representative Concentration Pathway (RCP) scenarios considered here include RCP 4.5 (Moderate Stabilization Scenario) and RCP 8.5 (High Emissions Scenario). The two different periods included in the projection studies include mid-century (2041-2070) and late-century (2071-2100). Five GCMs were considered here for projecting future climate with associated uncertainties reported through the ensemble mean and standard deviations in table 1.

Table 1: Climate Scenarios and Key Parameters

Scenario	Time Period	Temp. Change (°C)	Precipitation Change (%)	Water Stress Index
Baseline	1990–2020	—	—	0.32 ± 0.04
RCP 4.5 (2041–2070)	Mid-century	+1.8 ± 0.3	−12 ± 4	0.51 ± 0.06
RCP 8.5 (2041–2070)	Mid-century	+2.9 ± 0.4	−22 ± 6	0.67 ± 0.08
RCP 4.5 (2071–2100)	Late-century	+2.3 ± 0.5	−16 ± 5	0.58 ± 0.07
RCP 8.5 (2071–2100)	Late-century	+4.5 ± 0.7	−34 ± 9	0.81 ± 0.10

Ecosystem Service Assessment Methodology

These include provisioning of water, regulation of flow, erosion control, purification of water, provision of habitats, and recreational-cultural services. The selection of these ecosystem services was done depending on their relevance to the watershed and their measurability through existing data and modeling systems. Water flow simulations were conducted by the Soil and Water Assessment Tool (SWAT+) model calibrated and validated against measured streamflow data (NSE = 0.81, PBIAS = −3.7%). Provisioning of freshwater was measured as the amount of available water supply per unit area per year at each sub-basin level. Flow regulation was analyzed via flow variability and baseflow index. Erosion protection services were measured as the soil erosion rate using Revised Universal Soil Loss Equation (RUSLE). Water purification services were measured using total nitrogen and total phosphorus export coefficients for different hydrological flows. Habitat creation services were evaluated by applying Freshwater Habitat Integrity Index obtained through water flow modifications, water temperature, and sediment load.

Recreational/cultural services were estimated based on regional surveys of recreational water uses using benefit transfer.

Ecosystem service delivery shifts in response to the climatic scenarios were calculated based on the baseline condition and reported in terms of percentage change. Statistical differences among the scenarios were determined through one-way analysis of variance (ANOVA) with post hoc Tukey test comparisons. Hotspot identification of degraded sites was carried out using a vulnerability index, which combines the normalized service change scores in proportion to service demand. Potential mitigation strategies like riparian buffer creation, constructed wetlands, land-use zoning, low flow water release and integrated watershed management were simulated through scenario overlays. Table 2 below characterizes the ecosystem services analyzed.

Table 2: Key Freshwater Ecosystem Services and Climate Sensitivity

Ecosystem Service	Description	Climate Sensitivity	Threat Level
Water Provisioning	Supply of fresh water for drinking, irrigation, and industry	High is directly affected by altered precipitation	Critical
Flow Regulation	Moderation of river discharge and groundwater recharge	High drought and flood extremes	High
Erosion Control	Retention of soil and sediment in watersheds	Moderate linked to rainfall intensity	Moderate
Water Purification	Filtration and detoxification of pollutants	High temperature affects microbial processes	High
Habitat Provision	Support for biodiversity and aquatic life	High warming alters species composition	Critical
Recreation & Culture	Tourism, fisheries, aesthetic and spiritual values	Moderately affected by flow and water quality	Moderate

IV. Results

Baseline Ecosystem Service Characterization

The assessment of the ecosystem service provision at the baseline in the three sub-catchments indicates that there is considerable variability of services in terms of provision within each sub-catchment. The highest water provision capability was observed in the forested upper sub-catchment, supplying 54% of the total water yield in the watershed although it accounts for only 31% of the watershed area, in line with the high infiltration rates and evaporative losses from forested land use systems. The agricultural mid-catchment had the highest erosion susceptibility, with modeled sediment transport rates of 8.7 tons per hectare year, or about 2.4 times greater than that observed in the forested sub-catchment under the baseline climate condition. The lowest water purification ability was shown by the peri-urban lower sub-catchment, which has an annual total nitrogen export rate of 14.3 kg/ha/yr, about 3 times greater than the forested sub-catchment of 5.1 kg/ha/yr. The habitat integrity score was highest in the upper sub-catchment (0.78) compared to the low score of 0.41 in the lower sub-catchment due to the cumulative effects of hydrological alteration, sedimentation, and warming downstream.

Climate Change Impacts on Ecosystem Services

Predicted impacts of changes in freshwater ecosystem services for RCP 4.5 and RCP 8.5 scenarios are outlined in table 3 below. There are consistent decreases in all categories of ecosystem services, with their magnitude of changes growing in a non-linear manner towards late century and high-emission scenarios. The water provisioning category suffers the most as its decrease reaches -18.4% and -47.2%, respectively, for RCP 4.5 mid-century and RCP 8.5 late-century scenarios ($p < 0.001$). Similarly, water purification is predicted to decrease by -21.1% to -51.3% depending on the scenarios. Changes are mainly attributable to lower precipitation levels (-12% for near-term moderate scenario to -34% for late-century high-emission

scenario), higher evapotranspiration under global warming (+1.8 °C to +4.5 °C above baseline) and increased nutrient content caused by low river flows in table 3.

Table 3: Projected Changes in Freshwater Ecosystem Services Under Climate Scenarios (%)

Ecosystem Service	RCP 4.5 Mid (%)	RCP 8.5 Mid (%)	RCP 8.5 Late (%)	p-value (ANOVA)
Water Provisioning	-18.4	-31.7	-47.2	< 0.001
Flow Regulation	-14.6	-26.3	-39.8	< 0.001
Erosion Control	-9.2	-17.5	-28.6	0.003
Water Purification	-21.1	-35.4	-51.3	< 0.001
Habitat Provision	-16.8	-29.9	-44.5	< 0.001
Recreation & Culture	-11.3	-22.7	-33.9	0.001

Adaptive Management Strategy Effectiveness

An assessment of the impact of adaptive management approaches relative to the most likely mid-century scenario of RCP 8.5. Each of the strategies was associated with an improvement in ecosystem services, but not any one strategy managed to counterbalance the adverse impacts completely. Restoration of riparian buffers led to a 23.4% enhancement in erosion control and habitat creation, and was considered a high-priority and relatively costly approach. The creation of constructed wetlands resulted in improved water quality and flow management at around 19.7%. It was a costly venture, but it offered long-term gains. Sustainable land use zoning was associated with an improvement in ecosystem services of only 16.2%, but it was highly cost-efficient. An approach to integrated watershed management incorporating aspects from all four management approaches within a coordinated spatial governance structure proved to be the most effective overall approach, delivering an improvement of 28.1% over unmanaged conditions within the RCP 8.5 scenario in terms of total ecosystem services provided. It is, however, the costliest to coordinate and implement, involving the creation of cross-agency institutions. The findings support the notion that proactive management can help shield against ecosystem services reductions due to climate change in figure 2.

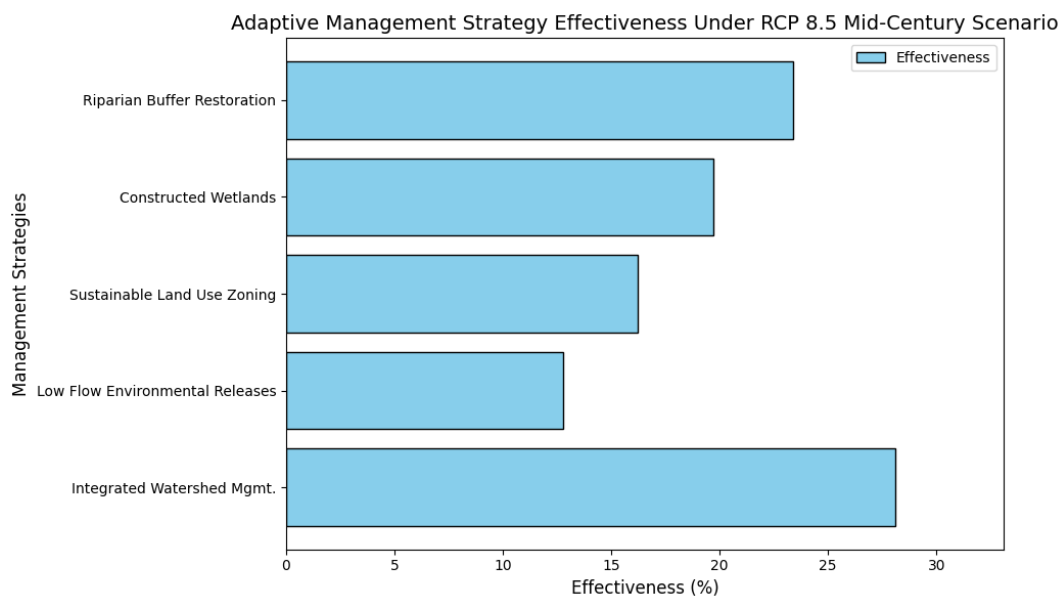


Figure 2: Adaptive Management Strategy Effectiveness under RCP8.5 Mid Century Scenario

V. Discussion

The outcomes of the study offer a comprehensive set of quantitative data showing that there are very significant and numerous risks for freshwater ecosystem services arising due to climate change scenarios of both medium and high emissions. The most important one is related to the non-linear nature of the increase in service damage for RCP 8.5 by the end of the century, which resulted in a decrease in water purification capability by more than half and water provisioning capability by almost half in comparison with the baseline state. These values correlate with the values from other studies in the same region (Bangash et al., 2013; Guo et al., 2021) but offer additional clarity due to a more detailed examination of multiple ecosystem services in a spatially-explicit manner. ANOVA test results ($p < 0.001$ for 4 out of 6 services) clearly indicate that the differences between the scenarios are caused by their divergence.

The spatial analysis showed that the peri-urban lower sub-catchment is the area with the highest vulnerability because of high demands and low supplies in terms of ecosystem services. This study result is important from a policy perspective, because it highlights the exact areas where management actions will produce the best results. The multi-stressors faced by this particular sub-catchment due to pressures of increased use of the land area, decline in streamflows, and pollutant loading demonstrate why such interactions between stressors were identified by Hering et al. (Hering et al., 2015), as well as Pham et al. (Pham et al., 2019), as important in managing water resources in the changing climate conditions. As predicted, integrated management was found to be the most successful approach to increasing the provision of all types of ecosystem services by 28.1%. Despite the success of this approach, however, the fact that it does not manage to overcome RCP 8.5 service losses by the end of the century emphasizes the importance of global measures to decrease emissions.

Some limitations of the present study need to be addressed. Firstly, the application of only one study watershed allows for the deepening of methodologies employed but limits the generalization of quantitative findings to other bioclimates. Ecosystem services evaluation employs a simplistic measurement of cultural/recreation services that cannot be quantified with the same precision as those related to hydrological aspects. Lastly, no autonomous adaptation by land users or water demands driven by socio-demographic factors have been considered in the analysis. Future research efforts should focus on broadening the applicability of this methodology to different watersheds and introducing the modeling of dynamic socio-economic processes in relation to climate change.

VI. Conclusion

Climate change is shown to impose significant effects on freshwater ecosystem services from all categories considered, with losses from water provisioning, water purification, and habitat provision expected to amount to or even surpass 45 percent by the late century under the RCP 8.5 scenario. These losses vary geographically, with peri-urban and agricultural catchment sub-catchments being the most affected by the combined effects of climate change and anthropogenic influences. The combination of hydrological modelling with ecosystem service assessment using multiple climate scenarios represents a valuable methodology that builds on the existing body of knowledge.

However, despite the considerable mitigation potential of adaptive management techniques, especially integrated watershed management, which can enhance total ecosystem service provision by up to 28.1% in a scenario of high emissions in mid-century, these actions still fall short of compensating for losses due to unabated emissions, thus emphasizing that both adaptation and mitigation have to be considered concurrently. Consequently, policy measures concerning water resource management have to account for climate change scenarios, ecological value assessment, and location-specific conservation priorities as key planning tools. The findings described above emphasize the importance of regarding freshwater ecosystem services not only as an ecological good but also as water infrastructure.

Some key directions for future work include: First, multi-catchment comparisons using standardized methods will permit the formulation of generalized functions of risk associated with ecosystem service

degradation due to climate change. Second, the inclusion of socioeconomic models of demand will allow for a better estimation of available services and distributional considerations. Third, a real-time system of monitoring based on remote sensing technologies together with on-ground sensors may assist in decision making processes. Fourth, including indicators of biodiversity in the analysis of climate-induced ecosystem services degradation will give a more holistic view of the situation.

Declaration Statement

Conflict of Interest: The authors declare no conflict of interest.

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Dataset Description: Hydrometeorological, land use, soil, and climate projection data used in this study were sourced from publicly available repositories including CHIRPS v2.0, SRTM, Soil Grids, and the CMIP5 archive, with no proprietary or restricted datasets employed.

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