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To cite this article: Fred Fokko Hattermann *et al* 2026 *Environ. Res.: Water* **2** 035004

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ENVIRONMENTAL RESEARCH WATER

PAPER



OPEN ACCESS

RECEIVED
6 August 2025

REVISED
23 January 2026

ACCEPTED FOR PUBLICATION
22 April 2026

PUBLISHED
22 June 2026

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Climate change in the upstream parts of the Amazon and Río de la Plata basins: impacts and adaptation in Bolivia's water–energy–food nexus

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Keywords: climate change impacts, water energy food nexus, hydroclimatic extremes, South-America, Bolivia, Amazon, Río de la Plata, undefined

Supplementary material for this article is available [online](#)

Abstract

The impacts of climate change are already evident in Bolivia, posing significant challenges to water and land management. This study is an attempt to provide science informed decision support within the water–energy–food (WEF) nexus by firstly quantifying potential climate change impacts on water resources, crop yields, and hydropower generation in two regions of Bolivia—the Upper Amazon and Upper Río de la Plata. In a second step, the simulated impacts define boundary conditions within which a suite of regionally developed adaptation measures was evaluated in collaboration with local stakeholders. The effectiveness of these measures under future climate scenarios was then assessed. The climate projections indicate spatially heterogeneous changes: while the windward slopes of the Andes facing the Amazon basin are projected to receive more rainfall, the Amazon lowlands and the Altiplano are likely to experience a decline. Consequently, water availability and crop yields are expected to decrease in the lowlands, while headwater regions may experience no change or even an increase. The possible decrease of river flow in the Upper Amazon is 25% under moderate climate change and 40% under high end climate change conditions by the end of the century, while there is a possible slight increase of river flow in the Upper Río de la Plata under moderate and a stronger one under high end climate change with a range of 0%–40%. Nevertheless, both basins are projected to face more frequent extreme events, particularly prolonged droughts. The findings further show that adaptive management within the WEF nexus can partially offset increased flow variability. However, such management must carefully balance competing demands for irrigation, electricity generation, and flood protection. The results also underscore the importance of global climate mitigation, as the severity of local impacts is considerably reduced under moderate warming scenarios.

1. Introduction

Many countries around the world, including Bolivia, are expected to face severe impacts from climate change, particularly on water resources and interlinked sectors within the water–energy–food (WEF) nexus (de Roo *et al* 2021, Gaetani *et al* 2023). These impacts threaten livelihoods and societal welfare.

As the climate system directly influences the hydrological cycle and vegetation processes, every additional increment of global warming results in escalating losses and damages (IPCC 2022). Moreover, the effectiveness of adaptation options diminishes with increasing levels of warming (IPCC 2023). Yet current progress on both emission reductions and adaptation remains insufficient (UN 2022, IPCC 2023).

Climate change impacts in Bolivia include glacial retreat, an increased frequency of extreme events such as floods and droughts, and greater variability in agricultural yields. Remote sensing data, including GRACE-FO satellite observations, reveal abnormally low soil moisture and groundwater storage across much of Central and Eastern South America, including the Bolivian Amazon lowlands (Rodell *et al* 2022). This situation threatens not only natural ecosystems, such as the Amazon rainforest, but also human water supply, as aquifers serve as a primary source for drinking water in Bolivia's Amazon and La Plata sub-basins (Guzmán Rojo *et al* 2024). Water-related risks are often compounded by political decisions and suboptimal land and water management. Since the ratification of the Paris Agreement in 2020, attention has turned toward aligning national adaptation and mitigation actions with global climate goals, formalized through nationally determined contributions (NDCs; UN 2015). Almost all NDCs recognize water as a core sector for adaptation, with many linking water to energy provision, food security, and forest conservation (UN Water 2010, Sadoff *et al* 2020).

Bolivia is currently formulating climate adaptation implementation and investment plans. Its NDCs encompass water, energy, forest, and agricultural sectors, including livestock. However, a major gap remains: the lack of comprehensive projections of climate risks in these sectors. To address this, robust climate impact assessments are essential, serving as inputs for cost-benefit analyses to prioritize effective adaptation strategies—especially in the water sector. The objective of this study is to provide a science-based climate risk assessment to support the development of resilient water management policies. As adaptation planning gains global momentum, our results highlight the importance of accounting for the dynamic interconnections within the WEF nexus.

2. Climate change and the WEF nexus

The literature consistently identifies climate change as a stress multiplier that intensifies existing trade-offs between water availability, energy production, and food security, particularly through altered precipitation regimes, increased drought frequency, and rising temperatures (Simpson *et al* 2022, Segovia-Hernández *et al* 2023). These climatic pressures propagate across sectors, for example by reducing hydropower reliability, constraining irrigation water supply, and increasing competition among users, thereby heightening systemic vulnerability (Hoff 2011). As a result, nexus-based approaches are increasingly positioned as essential for climate adaptation and resilience planning rather than as purely conceptual sustainability frameworks (Mabhaudhi *et al* 2024).

Despite methodological advances, many authors emphasize that governance failures remain a central barrier to effective nexus implementation. Sectoral silos, weak institutional coordination, and limited governance capacity are frequently identified as more restrictive than technical or data-related constraints, limiting the integration of nexus insights into real-world decision-making (Simpson *et al* 2022, Segovia-Hernández *et al* 2023). In Latin and South America, these challenges are particularly acute due to strong dependence on hydropower, high climate variability, and spatially uneven water availability, which together amplify climate risks across sectors (Bellfield 2015, Mahlke *et al* 2020). Regional studies therefore highlight the need for basin-scale, climate-informed governance and adaptive planning approaches to translate the WEF nexus into effective, integrated resource management, with a focus on restoring and protecting ecosystems like forests and wetlands (Recalde *et al* 2024).

3. Study areas

Bolivia features a highly diverse landscape, ranging from Amazonian rainforest in the northeast to the Andean Cordillera in the west. The Andes act as a topographic barrier to the warm and moist air masses from the Amazon, creating pronounced local and regional climatic variations. As a result, Bolivia comprises three distinct geographical regions:

- **Lowlands** (up to 500 m above sea level), covering around 60% of the national territory;
- **Altiplano and high Andes** (above 3500 m), comprising approximately 16%; and

- **Inter-Andean valleys and Eastern Slopes**, accounting for the remaining 24% (Abadi *et al* 2020).

The climate ranges from tropical in the northeast to semi-arid in the southeast, with mountainous tropical forests along the eastern Andean slopes and arid highlands in the west (Velpuri *et al* 2016). Average annual precipitation is approximately 1285 mm, with mean temperatures of 22 °C. For example, the Santa Cruz region receives about 1300 mm of rainfall annually with an average temperature of 25 °C, while the Tarija region records around 745 mm and 19 °C, respectively.

To represent Bolivia's physiographic diversity, this study focuses on two regions encompassing three river basins:

- **San Martín and Paraguá basins** (in Santa Cruz state), and
- **Guadalquivir basin** (in Tarija state) (figure 1).

The Guadalquivir basin is situated in the upper Bermejo catchment, ranging from 1595 to 4750 m elevation. As a tributary of the Río de la Plata flowing into Argentina, it covers 3334 km². The basin includes a large central valley encircled by hills and mountains to the north, west, and southeast (Moya *et al* 2021).

Approximately 50% of the cultivated area in the department of Tarija is dedicated to rainfed corn production, where the yields suffer from the increase in climate variability including droughts and floods. Due to deforestation of mountain slopes, erosion led to accumulation of soils with high fertility in valleys, usually occupying the banks of rivers. Therefore, important areas of crops are exposed to the overflow of rivers. Over the last years, the production of strawberries and raspberries in the central valley of Tarija represents a much better economic alternative than the production of potatoes, onions and other agricultural products.

The San Martín and Paraguá basins are part of the Iténez catchment in the Chiquitanía Norte region of Santa Cruz and belong hydrographically to the Amazon basin. The San Martín basin spans 33 155 km², while the Paraguá basin covers 27 170 km². Their forest areas are considered among the most productive in Bolivia (GAD Santa Cruz & AMDECRUZ 2020), and their ecological value is recognized by the establishment of the Noel Kempff Mercado National Park—the country's largest protected area.

Among the different environmental problems facing the department of Santa Cruz, deforestation and forest fires stand out. 18.65% (6908 971 hectares) of the department's territory have been deforested until 2021, and the fires find a significant synergy with the ongoing drought in the region. Deforestation leads to loss of the fertile soil layers, more surface runoff and as a result less infiltration and less groundwater recharge.

4. Data and methods

4.1. General workflow

In a first step, a series of workshops with Bolivian water and land experts was organized by the project partner GIZ Bolivia (German Corporation for International Cooperation). The focus was on water, food and energy security. Based on the discussions, model experiments were conducted with the aim to quantify climate change impacts, on the one hand, and the effectiveness of suggested adaptation measures, on the other. The detailed steps were:

1. Workshop with the regional stakeholders and experts in both study regions with the aim (i) to determine the climate change and WEF related problems and (ii) to identify a set of possible adaptation measures and strategies;
2. Data pre-processing and model set-up to quantify (i) climate change impacts on the current WEF nexus and (ii) the effectiveness of the proposed adaptation measures under climate change conditions
3. Presentation and discussion of the results in a second series of workshops in each study region
4. Based on the feedback from the regional experts and stakeholders, adjustment of the model implementation and simulations considering altered adaptation measures
5. Final workshops, dissemination and reporting

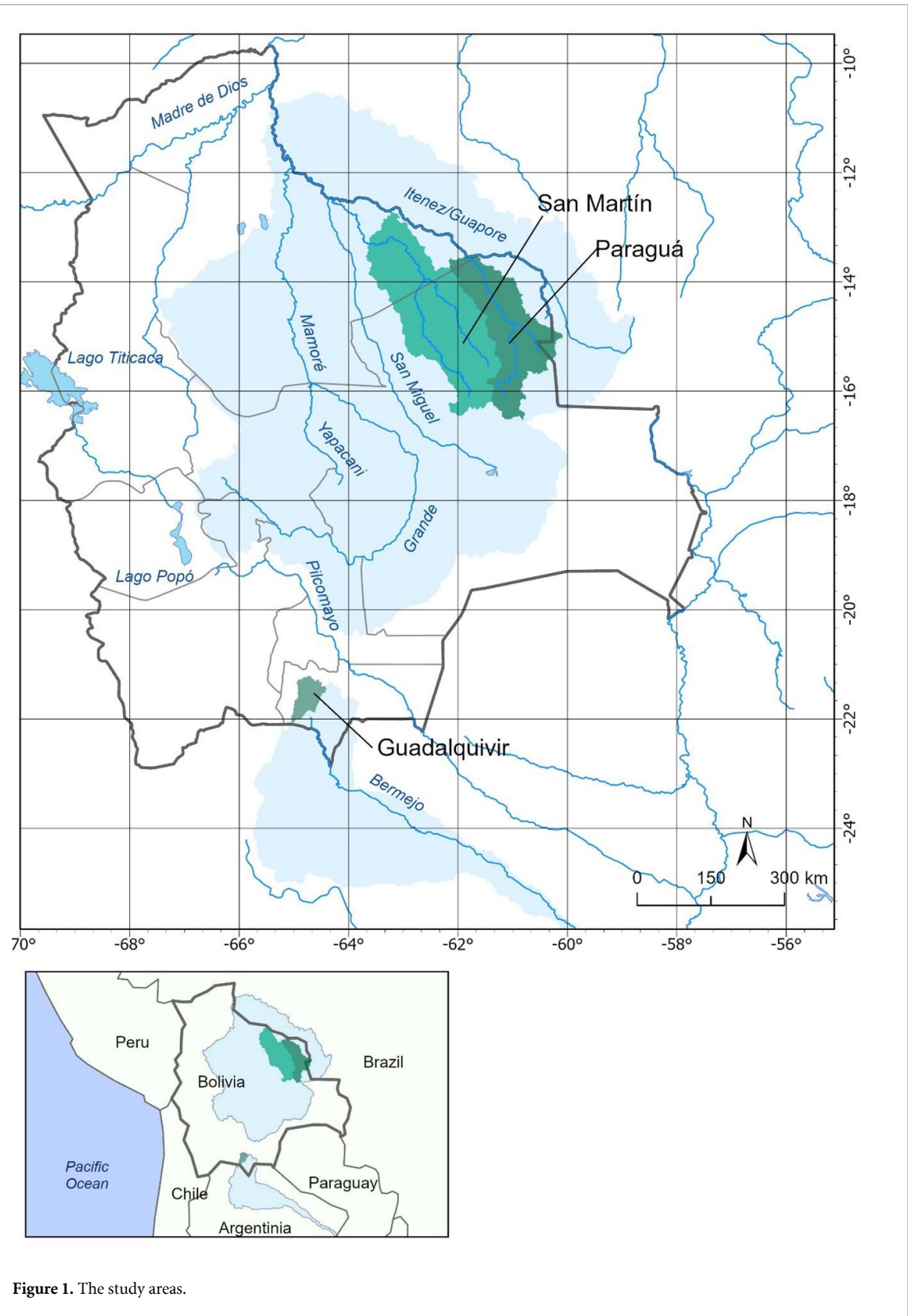


Figure 1. The study areas.

4.2. Climate data

The latest IPCC report (IPCC 2021) presents several future climate scenarios, referred to as shared socioeconomic pathways (SSPs), which span a range of additional radiative forcing levels from 2.6 to 8.5 W m⁻² by 2100. SSP1-2.6 represents a scenario with strong global mitigation efforts, while SSP3-7.0 and SSP5-8.5 represent futures with limited or no mitigation.

In this study, SSP1-2.6, SSP3-7.0, and SSP5-8.5 were selected to capture the broadest possible range of projected climate outcomes based on the latest generation of climate models. Climate data were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Phase 3 (Frieler *et al* 2024). This dataset includes an ensemble of ten global climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6), downscaled to 0.5° spatial resolution and bias-adjusted using the approach described by Lange *et al* (2021).

The standardized precipitation evapotranspiration index (SPEI) was applied to investigate drought development under scenario conditions. It accounts for the combined effect of precipitation deficit and increased atmospheric evaporative demand on drought severity (Vicente-Serrano *et al* 2010).

The eco-hydrological model calibration and the bias adjustment of climate data were based on $W5 \times 10^5$ reanalysis data—a merged dataset combining WFDE5 over land and ERA5 over ocean surfaces (Lange *et al* 2021). $W5 \times 10^5$ was chosen to ensure consistency with the bias adjustment applied to the ISIMIP dataset. A comparison of $W5 \times 10^5$ and ISIMIP data for the historical period is provided in supplementary material A1.

4.3. Eco-hydrological model

The Soil and Water Integrated Model (SWIM) was used to simulate climate change impacts and the effectiveness of adaptation measures. SWIM is a process-based eco-hydrological and water management model developed to assess climate and land use change impacts at regional scales (Hattermann *et al* 2011, Krysanova *et al* 2015). It integrates essential hydrological, vegetation, and management processes, including runoff generation, plant growth, carbon and nutrient cycling, and soil erosion.

The model also incorporates water management components, allowing the simulation of different reservoir operation strategies, including flood protection, hydropower generation, irrigation water supply, and low-flow augmentation (Koch *et al* 2013, Liersch *et al* 2019). Irrigation infrastructure and transmission losses are explicitly represented (Liersch *et al* 2023). The agricultural module simulates cropping sequences, fertilization, harvests, and associated nutrient flows. Vegetation dynamics are modeled for a variety of land cover types, including crops, forests, grasslands, and shrublands.

This integrated framework enables simulation of the interrelated processes and feedbacks within the WEF nexus on a daily time step. SWIM employs a three-level spatial hierarchy—catchment, sub-basin, and hydrotope (defined by unique combinations of land use, soil, and topography).

Model calibration was conducted using observed discharge data provided by regional authorities, with results presented in supplementary material A2. In the Guadalquivir basin, model performance was additionally validated against observed water levels and volumes of the San Jacinto Dam. The dam has a maximum capacity of 63.0 million m³, a dead storage of 17.8 million m³, as a result an active storage of approximately 45.0 million m³ and a 54.15 m maximum fall height for hydropower production. The results are shown in figure 2.

Due to limited availability of regional crop data, simulated yields were compared with national agricultural statistics from FAO (2024) and adjusted accordingly.

4.4. Management scenarios and adaptation measures

To identify feasible and context-specific adaptation strategies, a series of workshops and consultations was conducted with local stakeholders in both regions. Based on this participatory process, five regionally tailored adaptation measures were selected:

- For the **San Martín and Paraguá** basins (Santa Cruz):
 1. Restoration of fire-affected areas
 2. Improvement of livestock practices, including fodder production
- For the **Guadalquivir** basin (Tarija):
 3. Improved reservoir operations prioritizing irrigation
 4. Expansion of high-value crop production, especially grapes and strawberries
 5. Enhanced flood protection measures under climate change conditions

Forest restoration actions include natural forest regeneration ('passive restoration') and the implementation of sustainable land use practices ('active restoration'). Active restoration strategies focus on areas that, according to the severity analysis, have not managed to initiate natural regeneration processes, with

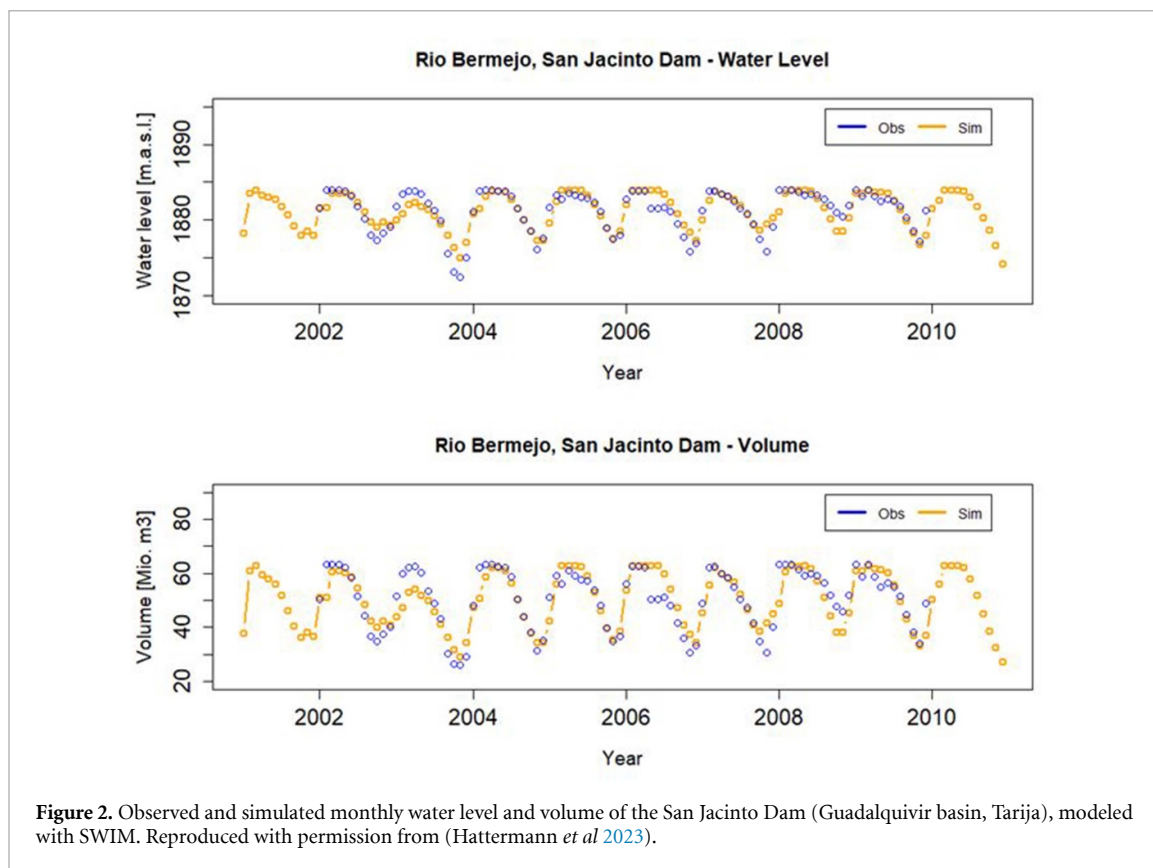


Figure 2. Observed and simulated monthly water level and volume of the San Jacinto Dam (Guadalquivir basin, Tarija), modeled with SWIM. Reproduced with permission from (Hattermann *et al* 2023).

the disturbance being greater than the responsiveness of the ecosystem. Improved livestock practices include cattle husbandry with extended grass crops (including sorghum and legumes) in silvopastoral systems and/or windbreaking drapes, conservation of fodder with silos or hay and the provision of mineral salt for cattle.

The Tarija case study, in particular, illustrates key WEF nexus interdependencies. This is why it is explored in more detail below.

Three main **management scenarios** were defined (table 1):

- **Baseline scenario:** reflects the current status quo. The primary objective of reservoir operation is hydropower generation, with irrigation as a secondary priority. No infrastructure improvements are implemented, and climate change is not considered.
- **No-adaptation scenario:** the dam infrastructure remains unchanged. No expansion of irrigated areas occurs, and water allocations remain as in the baseline scenario. However, hydropower operations are adapted to new flow regimes under climate change.
- **Adaptation scenario:** the priority shifts to irrigation water supply, while hydropower becomes a secondary objective. By 2050, parts of the irrigation pipeline are upgraded to increase flow capacity and reduce transmission losses. Climate change influences reservoir inflows.

The trade-offs and synergies of the measures were quantified through model simulations that altered reservoir operations and water allocations accordingly.

The reservoir's active storage volume is thus subject to varying management priorities. In a flood protection mode, a larger portion of the reservoir's active storage capacity is reserved for flood prevention, reducing the volume available for irrigation and hydropower. Conversely, when focusing on hydropower, as much water as possible is stored during the rainy season to maximize hydropower production in the dry season. The latter can support irrigation downstream of the reservoir in the dry period, but would mean less water is available for irrigation in the same period from the reservoir, as priority is on hydropower. Thus, in the dry period hydropower and irrigation from the reservoir are competing priorities. The thresholds considered are:

Table 1. Definition of adaptation measures and scenarios for the Tarija region.

Scenarios	Change of crop(no irrigation)	Irrigation of strawberries	Change of reservoir management
Baseline (no CC) Noadaptation (with CC)	Corn cultivation	Strawberry cultivation (16 ha) with flood irrigation	Priority (first operational objective) on hydropower generation with generation peaks in rainy season, second objective is irrigation (no flood control)
Adaptation (with CC)	Wine	Strawberry cultivation (3000 ha) with drop irrigation	Priority on irrigation, second goal hydropower generation (peak generation in rainy season, no flood control).

- >45 million m³ (high storage, posing potential flood risk)
- <5 million m³ (low storage, risking water shortage for irrigation and energy)

While there are many measures thinkable when looking on flood protection (dykes, polders, early warning etc), we focus here on improved reservoir management.

5. Results

5.1. Climate change impacts on air temperature

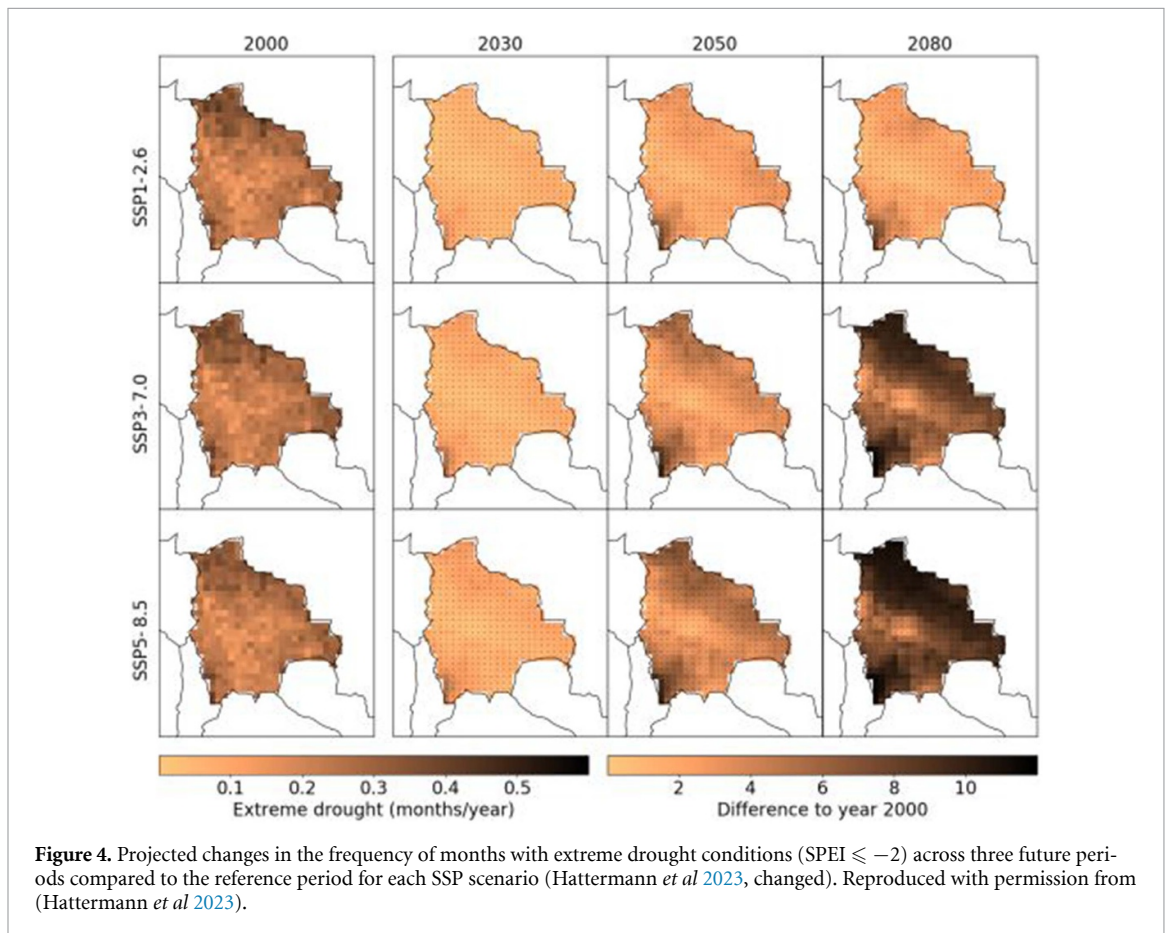
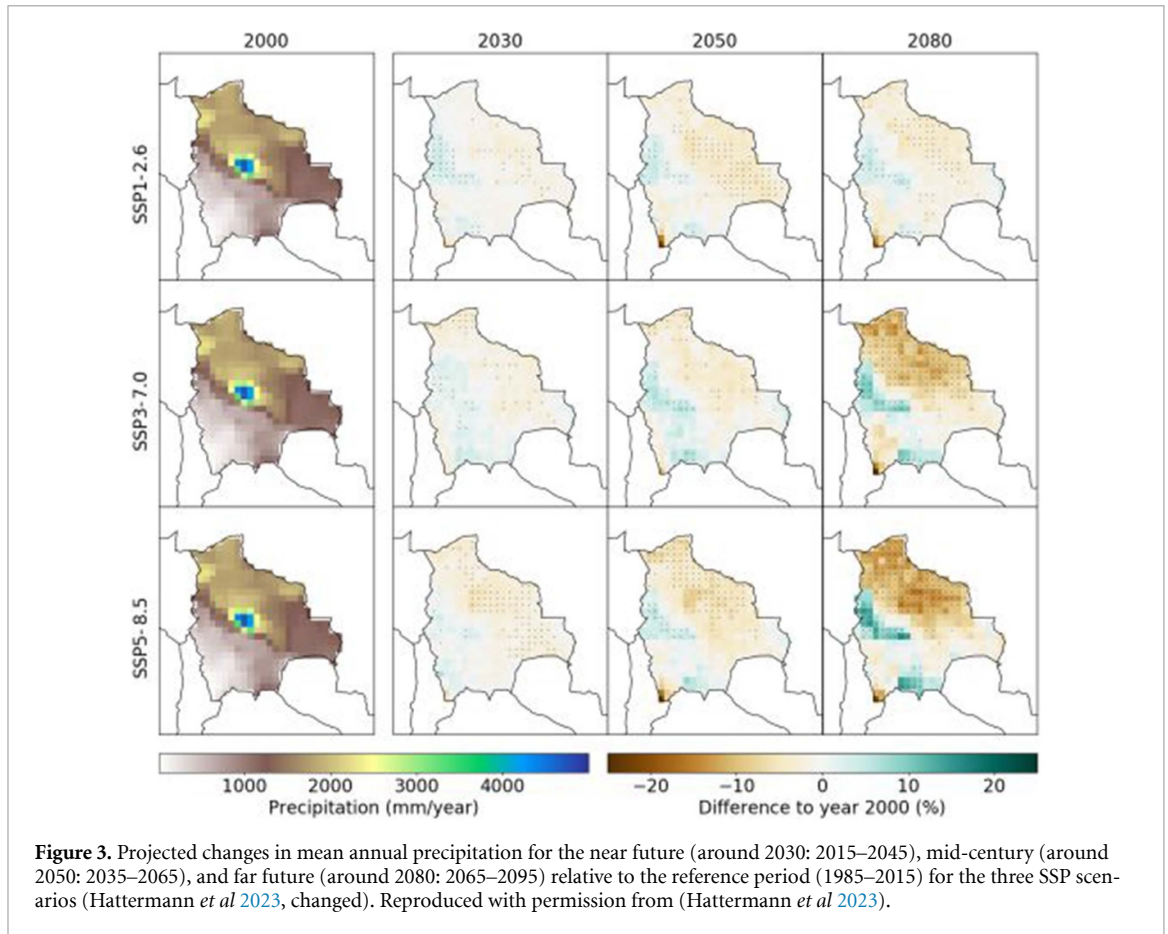
Air temperature projections indicate a significant increase in annual mean temperatures across all three SSP scenarios over the 21st century compared to the reference period (1985–2015) (figure A4(a) in the supplementary material). The climate projections begin to diverge after the 2030s. SSP3-7.0 and SSP5-8.5 show a continuous increase in temperature throughout the century, whereas warming stabilizes under SSP1-2.6 after the 2050s.

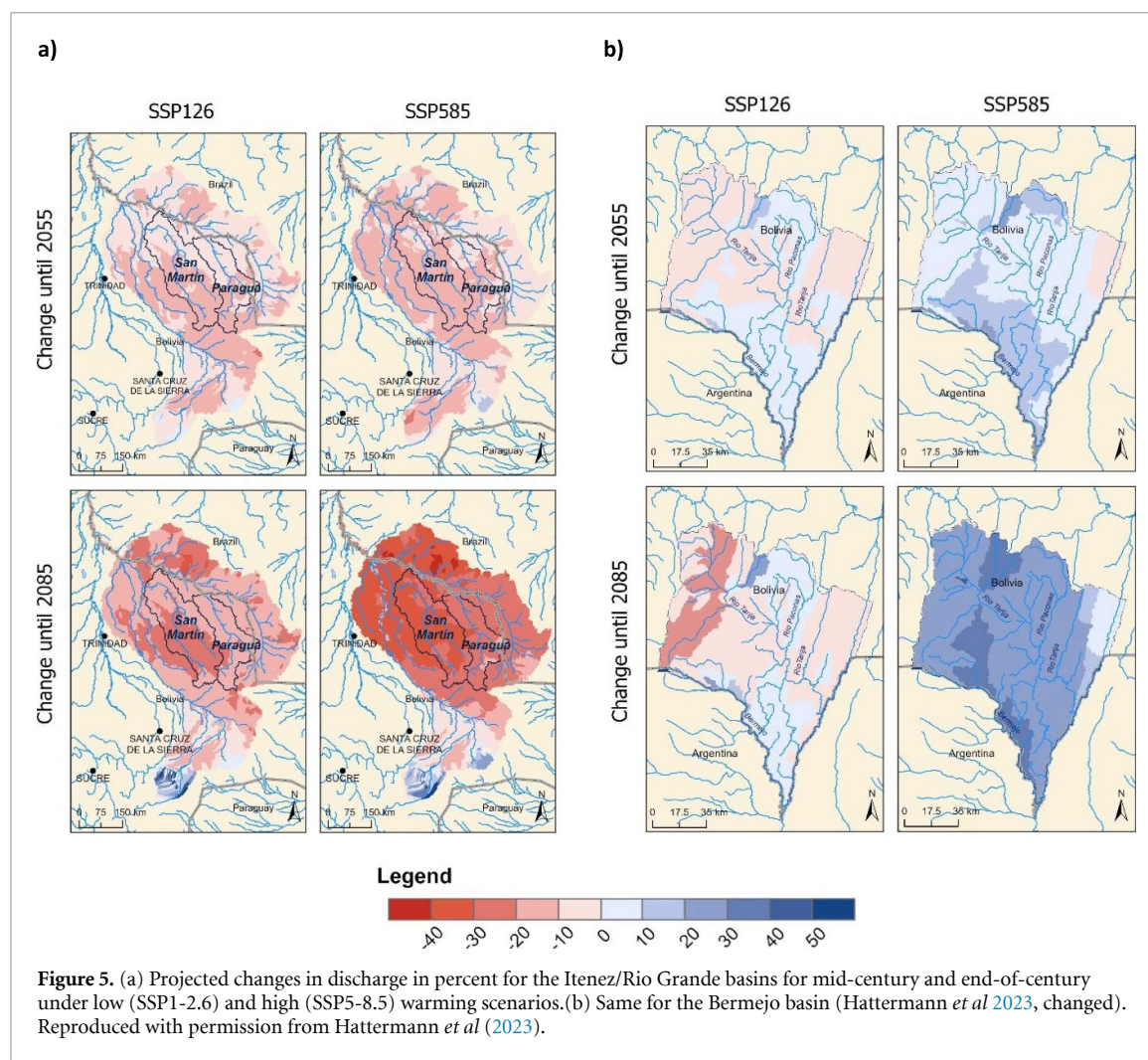
For the far future (2065–2095), compared to the reference period, annual mean temperatures are projected to rise by 2.0 °C–3.4 °C under SSP1-2.6, 3.8 °C–6.9 °C under SSP3-7.0, and 4.4 °C–8.2 °C under SSP5-8.5. The multi-model median change is +2.5 °C (SSP1-2.6), +4.7 °C (SSP3-7.0), and +5.8 °C (SSP5-8.5). Spatially, the strongest warming is projected for the southern Altiplano and the northern lowlands (see figure A5 in the supplementary material). As a consequence of this warming, the frequency of very hot days is projected to increase (figure 4(b) in the supplementary material), while frost days are expected to decrease in all scenarios (figure 4(c) in the supplementary material). Maps of projected changes in mean annual temperature and very hot days are available in supplementary material (figures A5 and A6).

5.2. Climate change impacts on precipitation

Across all scenarios, the multi-model median indicates a decreasing trend in mean annual precipitation over Bolivia, with average reductions of 30 mm (SSP1-2.6), 68 mm (SSP3-7.0), and 67 mm (SSP5-8.5) for the far future (2065–2095) relative to the reference period (figure 3). A large ensemble spread highlights substantial uncertainty among climate models. Seasonal shifts are also evident: precipitation is projected to decline more during wetter months, particularly from September to November under SSP3-7.0 and SSP5-8.5. A downward trend in precipitation during December–February is also expected in the latter half of the century.

Importantly, these precipitation changes vary regionally (figure 3). The analysis highlights areas with high model agreement (defined as more than 75% of CMIP6 models agreeing on the sign of change, indicated by dots in figure 3). The largest decreases are projected in the northern lowlands, which also experience the highest warming. In contrast, increases in precipitation are expected in the northern Bolivian Altiplano and the south-eastern slopes of the Andes, particularly in the Tarija department. A robust and concerning result across all scenarios is the projected increase in extreme drought events using the SPEI as indicator (figure 4).





Maps of projected changes in heavy precipitation days and drought frequency are provided in supplementary material (figures A7 and A8).

5.3. Impacts on hydrological processes and crop yields

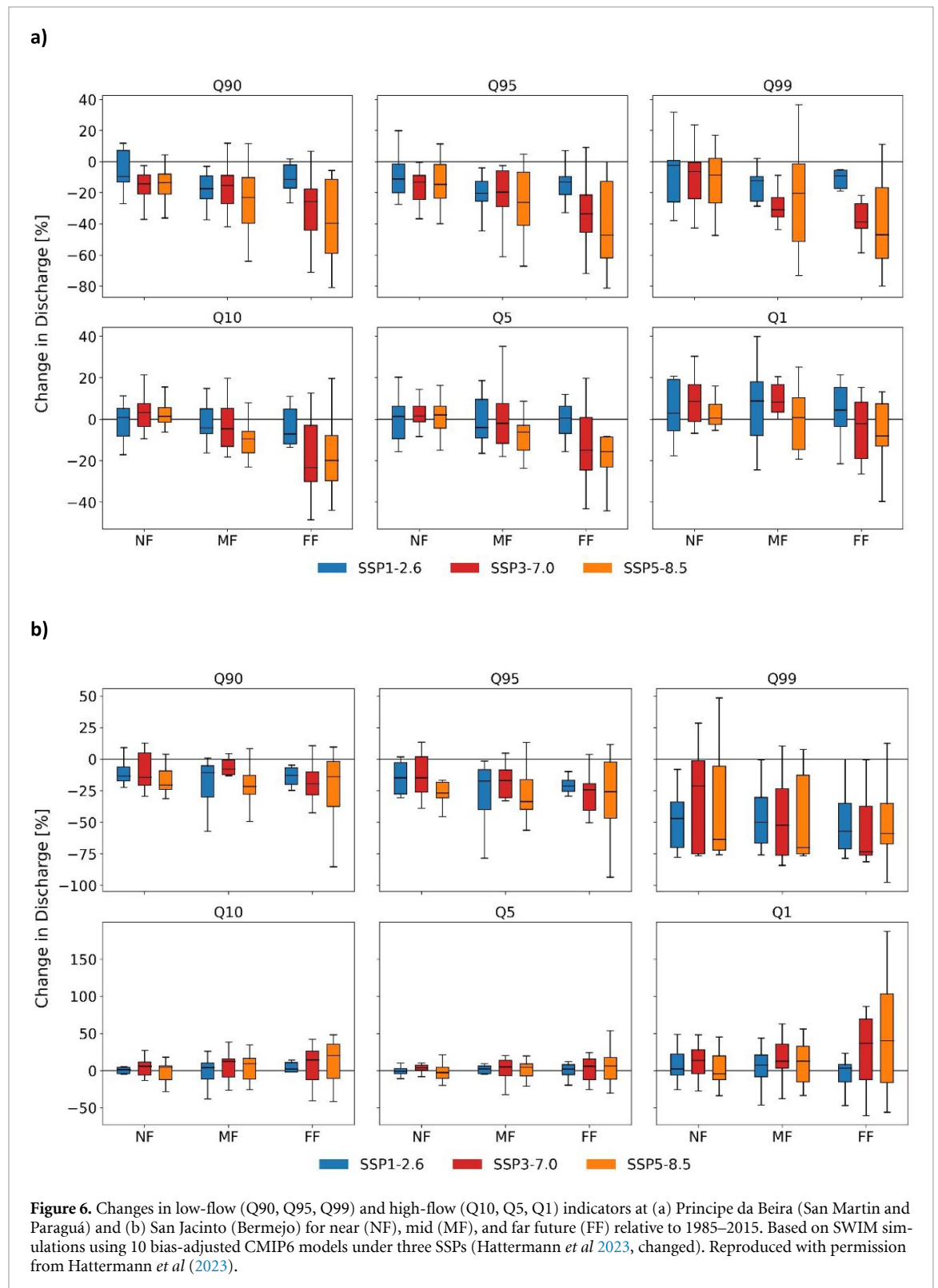
To translate climate changes into hydrological and agricultural impacts, the SWIM model was applied. Given the regional variability and associated uncertainty, projected impacts on water resources and vegetation differ notably between Tarija and Santa Cruz, yet some robust patterns emerge.

In the Itenez basin, a consistent decrease in discharge is projected—down to -15% by mid-century and -25% by century's end under SSP1-2.6. The decrease is even more severe under SSP5-8.5, reaching -25% by mid-century and up to -40% in the San Martín and Paraguá basins by the end of the century (figure 5(a)).

In the Bermejo basin, modest changes are projected under SSP1-2.6, ranging from -5% to $+10\%$ by mid-century. Under warmer scenarios, more pronounced increases in flow are projected, reaching up to $+20\%$ mid-century and $+40\%$ by century's end under SSP5-8.5 (figure 5(b)).

Increasing drought frequency (figure 4) also exacerbates low-flow conditions across both basins. Figure 6 presents changes in low-flow (Q90, Q95, Q99, with 90%, 95% and 99% of the flows above) and high-flow (Q10, Q5, Q1, with 10%, 5% and 1% of the flows above) indicators. All low-flow indicators show substantial reductions in discharge, particularly under SSP5-8.5 in the far future, with Q95 and Q99 flows reduced by up to 50%. High flows generally increase in the Bermejo basin, whereas moderate high flows (Q10 and Q5) show little or no change in the Itenez basin. The extreme high-flow indicator (Q1) shows slight increases until mid-century under SSP1-2.6 and SSP3-7.0.

In the Bolivian lowlands, declining precipitation and increasing drought risk are projected to adversely affect crop yields (soybean) and pasture (figure 7). SSP1-2.6 shows only modest declines, while

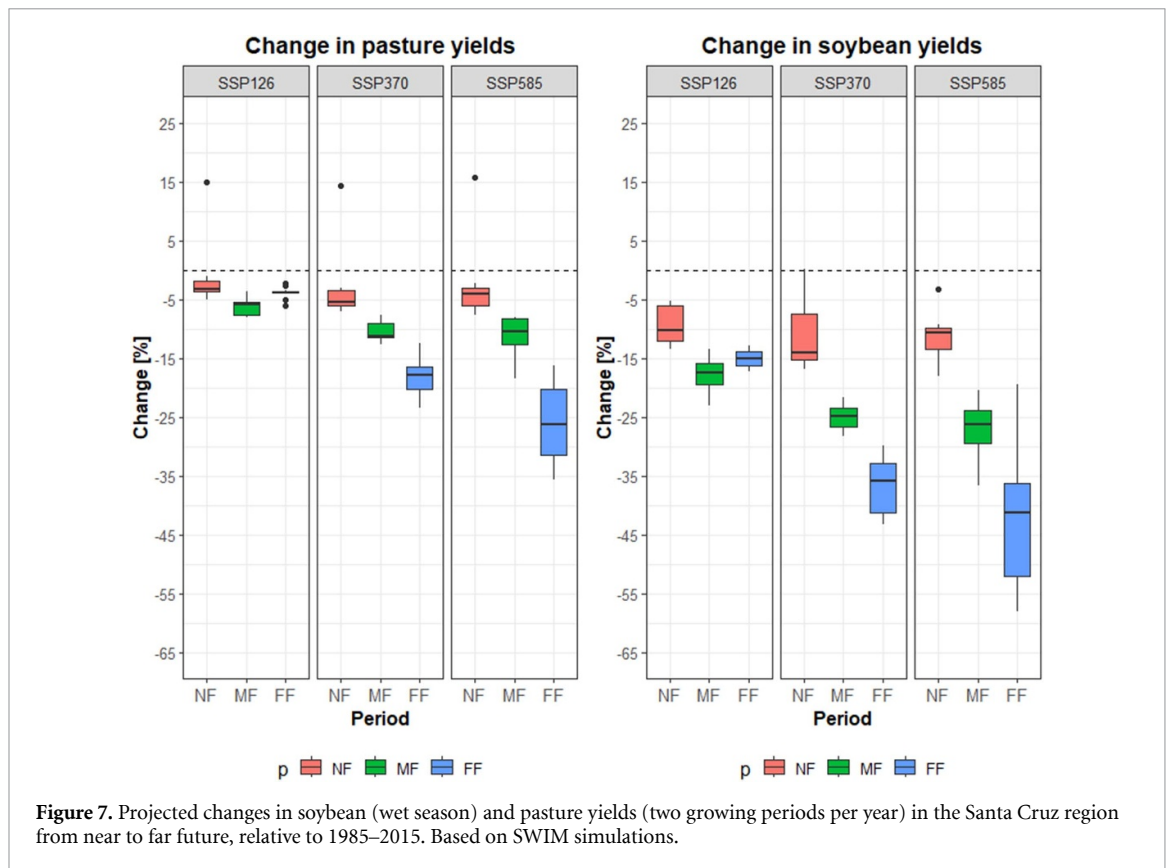


the high-end SSP5-8.5 scenario results in substantial reductions, particularly by the end of the century—exceeding 25% for pasture and 45% for soybean, assuming no adaptation or management changes. In contrast, Bermejo may see slight yield increases due to warming and localized precipitation increases.

Further details on changes in seasonal flows and reservoir inflows for the Santa Cruz region are available in supplementary material (section A4).

5.4. Adaptation measures integrating water and land management

Among the set of measures discussed with local stakeholders and experts in the Guadalquivir Basin (Tarija), adapted reservoir management was selected as a key example to illustrate the interdependencies



and trade-offs within the WEF nexus. This approach integrates irrigation, flood protection, and hydro-power generation. Given the projected increase in flood risk under climate change, prioritizing flood protection was considered an additional adaptation strategy (see figure 6). In this mode ('Flood protection'), a larger portion of the reservoir's active storage capacity is reserved for flood prevention, reducing the volume available for irrigation and hydropower. Conversely, in the 'Constant electricity' strategy, as much water as possible is stored during the rainy season to maximize hydropower production in the dry season. The reservoir's active storage volume is approximately 45 million m³, and this volume is subject to varying management priorities.

The combined impacts of climate change and reservoir management on storage levels and electricity production are presented in figure 8. A key finding is that, under scenario conditions without major changes in annual inflow, the reservoir can buffer increased variability. Notably, management strategies have a greater influence than climate scenarios across the near, mid, and far future, as can be seen from the nearly unchanged curves for actual storage and hydropower generation in the various time horizons and scenarios. The starkest contrast is observed between the 'Constant electricity' scenario—which maximizes rainy season storage—and the 'Flood protection' scenario—which prioritizes emptying the reservoir to prepare for potential flood events.

In the 'Adaptation' scenario, where irrigation expansion is a goal, more water is stored for dry-season irrigation of 3000 ha of strawberries. In contrast, the 'No adaptation' scenario stores less water, prioritizing hydropower generation.

As expected, the 'Constant electricity' scenario yields the highest electricity production, particularly during the dry season (figure 8(b)), due to increased water release in summer following winter storage. In contrast, the 'Flood protection' scenario results in the lowest electricity generation, since more storage capacity is reserved to buffer potential flood events.

To assess how much additional irrigation demand can be met from the reservoir, and to estimate the potential expansion of irrigated strawberry cultivation, we simulated a stepwise increase in irrigated area in the Bermejo basin from 3000 ha to 7000 ha. Two irrigation practices were considered: (i) conventional flood irrigation (currently practiced in the basin), and (ii) modernized drip irrigation. Figures 9 and 10 present how often reservoir storage thresholds are exceeded under both irrigation methods and varying extents of irrigated area (>45 million m³ high storage threshold, and <5 million m³ low storage threshold).

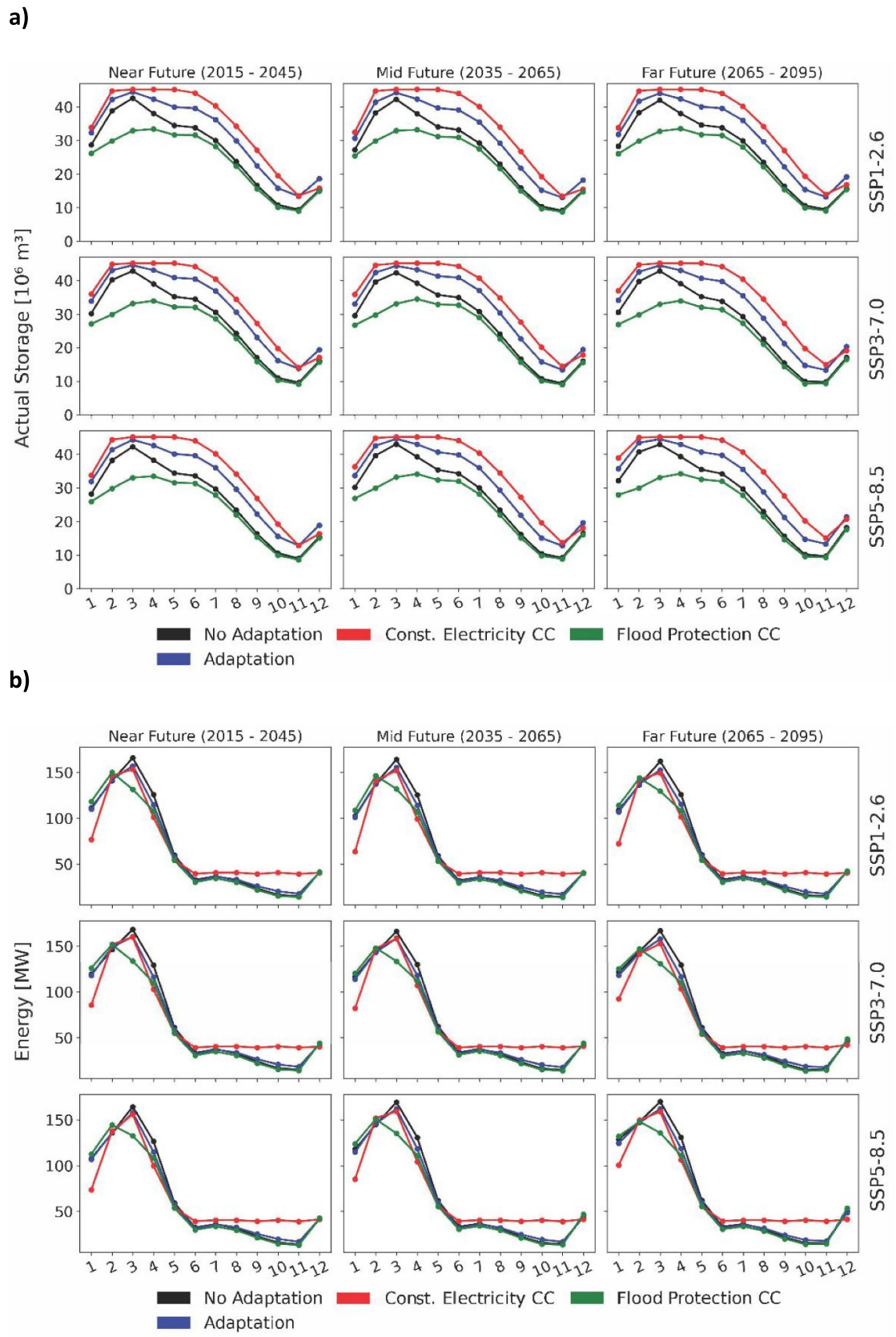
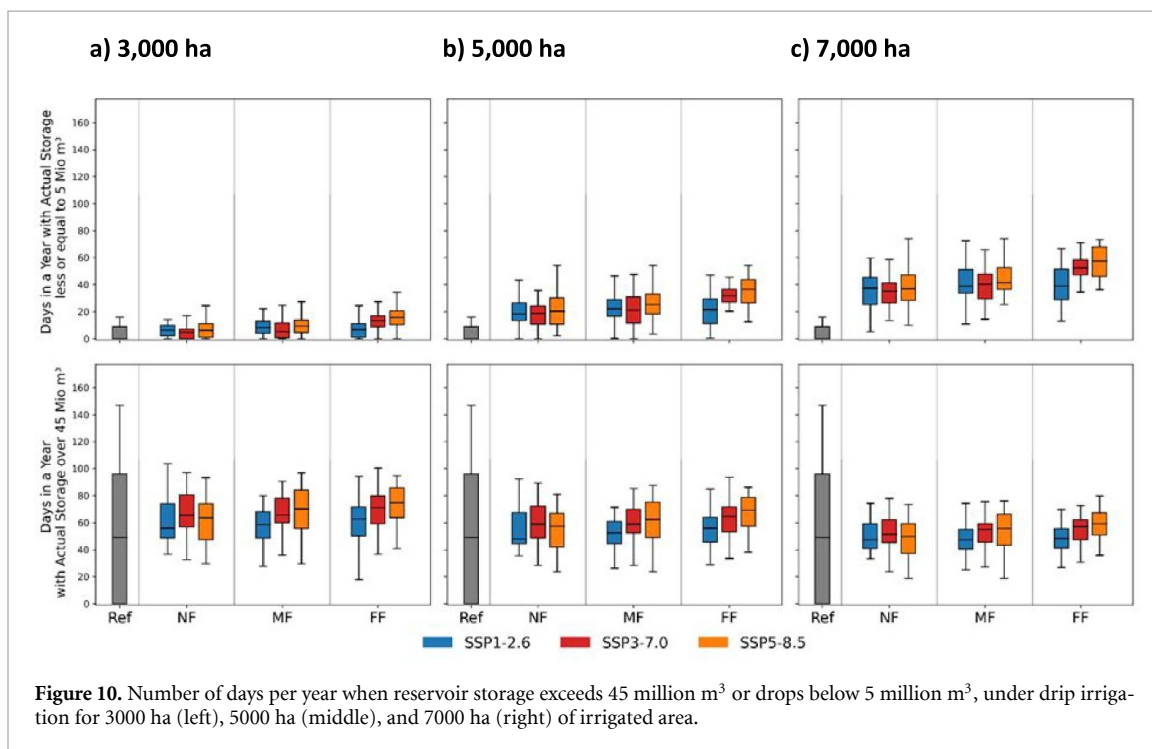
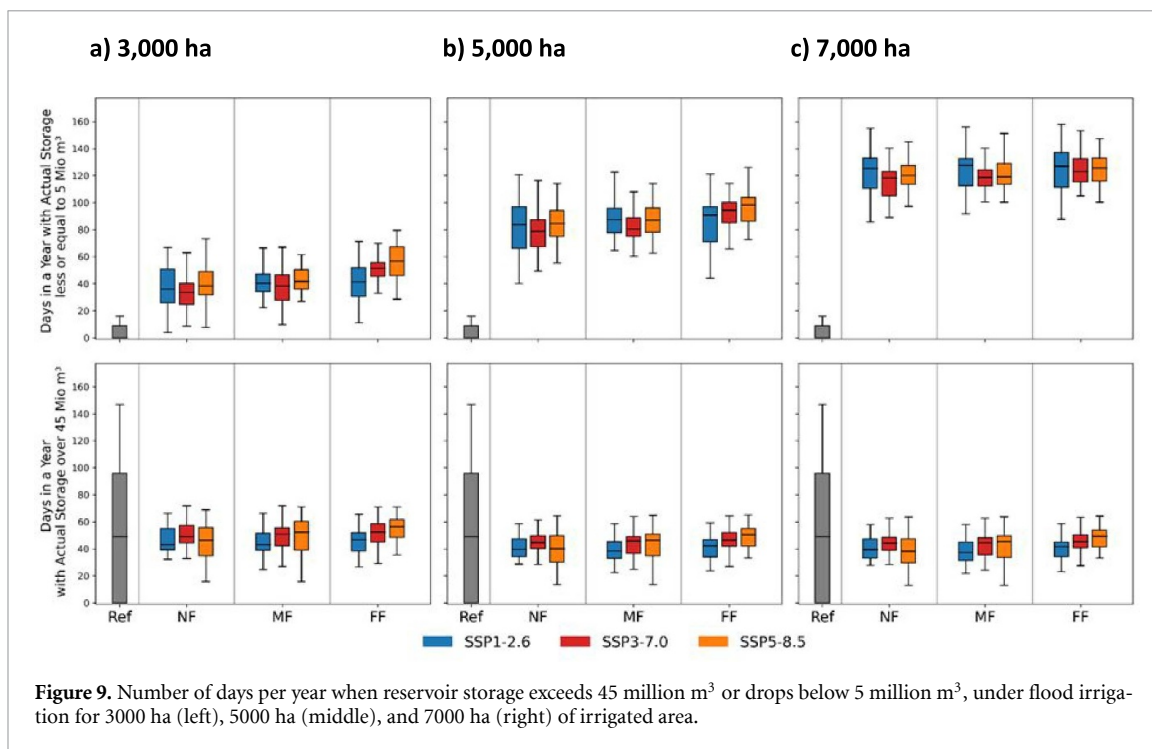


Figure 8. Illustration of the effects of different management strategies on reservoir storage (a) and hydropower generation (b) under three climate scenarios. The simulations are based on the SWIM model forced by an ensemble of 10 bias-adjusted CMIP6 models for SSP1-2.6, SSP3-7.0, and SSP5-8.5.



The model results indicate that irrigation demand can be met in most scenarios when expanding up to 3000 ha. However, under flood irrigation, increasing the area to 7000 ha leads to significant stress during the dry season, with the reservoir often dropping below critical storage levels. In contrast, drip irrigation substantially reduces water demand and maintains more stable storage conditions.

The results illustrate that drip irrigation leads to greater water sustainability in the reservoir system. For example, under flood irrigation, the number of days with storage below 5 million m³ increases to over 100 d per year by the end of the century (figure 9). With drip irrigation, this number remains below 50 d on average (figure 10), even under high irrigation demand and adverse climate conditions. Further analysis of the irrigation scenarios and their implications for reservoir storage dynamics is provided in the supplementary material (section A5).

6. Discussion

Projected climate warming in Bolivia exceeds the global average, consistent with previous studies based on CMIP5 simulations (Seiler *et al* 2013). Unlike many studies in the past, this study attempts to identify sustainable strategies for adapting to climate change by taking a holistic approach that considers all important processes and actors in the WEF nexus. The measures considered were selected so that they apply to the regional and socioeconomic context and included for the San Martín and Paraguá basins (Santa Cruz) restoration of fire-affected areas and improvement of livestock practices including fodder production and for the Guadalquivir basin (Tarija) improved reservoir operations prioritizing irrigation, expansion of high-value crop production, especially grapes and strawberries, and enhanced flood protection measures under climate change conditions by changing reservoir management.

Future projections indicate reduced precipitation over the lowlands and an increase along the eastern slopes of the Andes. The projected decrease in lowland precipitation aligns with observed negative trends in the Madeira River basin (-5.1 mm yr^{-1}) reported by Da Motta-Paca *et al* (2020), while increases over the Andes correspond with positive trends in the southeastern slopes and northern Altiplano as found by Torres-Batló and Martí-Cardona (2020), Segura *et al* (2020), and Seiler *et al* (2013).

Precipitation projection uncertainty likely stems from model difficulties in simulating the region's complex climatic drivers. These include large-scale circulation (e.g. the latitudinal shift of the Atlantic Intertropical Convergence Zone, the South American Monsoon System, and the Bolivian Highlands) and local dynamics such as upslope and downslope moisture transport, interacting with the rugged Andean topography (Garreaud 2009, Espinoza *et al* 2020, Segura *et al* 2020). The influence of El Niño–Southern Oscillation further complicates the regional precipitation signal (Poveda *et al* 2020), contributing to significant biases in CMIP6 model outputs (Arias *et al* 2021).

As a result, climate impacts on water resources and crop yields vary substantially between regions. In Tarija, future projections suggest stable or increased water availability under SSP3-7.0 and SSP5-8.5, but also show substantial uncertainty and a potential decrease under moderate warming (SSP1-2.6), along with an overall trend toward increased drought risk. In contrast, all scenarios indicate declining water availability in the lowlands of Santa Cruz, with more severe impacts under higher warming pathways. It is therefore a significant and worrying finding that also under reduced global warming conditions, runoff generation and discharge in the Upper Amazon of Bolivia will decrease.

It is important to note that the uncertain increase in water availability in Tarija diverges from the findings of Álvarez *et al* (2021), who projected water scarcity in the region, though their analysis was based on only two CMIP5 models.

Remarkable is that the proposed measures in the Guadalquivir basin (Tarija), have the ability to counteract undesirable impacts of climate change, if we succeed in preventing excessive global warming, but this capacity comes with trade-offs among water users within the WEF nexus. As a result, reservoir operations must be robust and adaptable to changing future conditions (Loucks and van Beek 2017).

This spatial heterogeneity calls for flexible adaptation strategies in Bolivia's NDCs and related policy instruments. Adaptation and mitigation measures therefore should highlight the need for basin-scale, climate-informed governance and adaptive planning approaches to translate the WEF nexus into effective, integrated resource management, with a focus on restoring and protecting ecosystems like forests and wetlands (Recalde *et al* 2024).

7. Conclusions

The goal of this study was to (i) quantify climate change impacts and (ii) identify sustainable adaptation strategies within the WEF nexus in the Upper Amazon and Upper Río de la Plata basins in Bolivia. Climate change is a global challenge, but its impacts unfold locally, and adaptation measures have to apply to the regional context. This study highlights the importance of regional-scale analyses to inform adaptation strategies. In the headwaters of the Amazon and La Plata Rivers, located in the Andes, precipitation may increase, while the lowlands may face declining rainfall. This spatial disparity alters water availability across the WEF nexus and necessitates regionally tailored water and land management strategies.

Adaptive water management offers a means to mitigate adverse climate impacts—provided that climate change does not exceed critical thresholds. Moreover, the projected decline in precipitation in the Andean foothills and lowlands threatens sensitive ecosystems, including the Amazon rainforest, which is already under pressure from deforestation and agricultural expansion. Further research is needed to assess how combined climatic and anthropogenic stressors affect these vulnerable landscapes.

Lastly, the results underscore the importance of climate change mitigation: both water scarcity and hydrological extremes intensify with increasing global temperature. Reducing greenhouse gas emissions remains essential to limit the adverse impacts on Bolivia's water systems and ensure sustainable development.

Acknowledgments

This study benefited from the contributions of several institutions and experts. The authors gratefully acknowledge the support of the Directorate of Planning, Vice Ministry of Water Resources and Irrigation (Dirección de Planificación, Viceministerio de Recursos Hídricos y Riego), the National Meteorological and Hydrological Service (Servicio Nacional de Meteorología e Hidrología), the Departmental Autonomous Government of Santa Cruz (Gobierno Autónomo Departamental de Santa Cruz), and the Departmental Autonomous Government of Tarija (Gobierno Autónomo Departamental de Tarija).

This work is part of the project 'Climate risk assessment to identify robust adaptation strategies in the water sector in Bolivia' (available for download [<https://www.bivica.org/file/view/id/6432>]), funded by the German Cooperation through the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Supplementary Material available at <https://doi.org/10.1088/3033-4942/ae6368/data1>.

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