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Modeling water availability under climate change scenarios: a systemic approach in the metropolitan area in Morelos, México

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The research investigates integrated water management with complex socio-environmental interactions in worsening climate change scenarios. The proposed methodology involves the integration of Atmosphere–Ocean General Circulation Models (AOGCM) with Water Evaluation and Planning models (WEAP) to ensure water availability in the future. Two Shared Socioeconomic Pathways (SSP) integrate environmental, socioeconomic, and political elements under climate change scenarios with greater rainfall variability, extreme droughts, and floods in the metropolitan area of Morelos, located in the Center of México. Water availability in this region, along with population growth, industrialization, service activities, and agriculture, depends on forest conservation in the Ravines System of Northwest Morelos (RSNM). Public policy lacks interdisciplinary socio-environmental development, which prioritizes unsustainable economic growth overexploiting aquifers and polluting rivers. Official data from national and state governments do not reflect water conditions, and aquifer statistics date back decades. The majority of the analyzed models predict a delay in the monsoon, higher temperatures, extreme climate events, depletion of groundwater, and severe water scarcity during the hot months, rendering them unable to meet the increasing demand. This research provides valuable insights into the complex socioeconomic dynamics of a region with future water scarcity, which could be useful for similar conditions in the Global South.

KEYWORDS

water models with climate change scenarios, Ravines System of Northwest Morelos, climate extremes, socioenvironmental impacts on water, groundwater availability, water scarcity, chaotic urbanization, global south

1 Introduction

Mexico is experiencing a water crisis and pollution in nearly two-thirds of its municipalities ([Healing Waters International, 2023](#)). The Global Risk Report 2024 indicates that Mexico is the country with the fourth highest risk of climate change and the second in terms of vulnerability ([World Economic Forum, 2024](#)). The interaction of socio-environmental factors in rapidly growing cities has limited clean water supply in the Global South ([Watch, 2022](#)). About 36% of the world's population (2.4 billion people) live in water-scarce regions, and half of them will experience severe water shortages ([UN Habitat, 2022](#)). Climate change with higher temperatures and alteration of the precipitation cycle has increased water stress due to dangerous extreme events

(droughts and floods; IPCC, 2014; UN-WATER, 2019; Kikstra et al., 2022). National water policies have focused on solving problems related to supply and demand through a centralized, mercantile, and infrastructure approach. Inefficient planning, management, unfair appropriation of rents for private concessions, high pollution, and corruption hindered the human right to water, sanitation, and a healthy environment. Multiple policies tried to correct water management; however, most of them aligned with power struggles, gaps in the application of norms, surveillance, and sanction, and a lack of professional training (García Barrios and Mozka Estrada, 2023).

Climate change is closely associated with the hydrological cycle, rainfall variability, extreme events, and the predictability of water availability, aquifer recharge, economic activities, and livelihoods. The alteration of quantity and quality of rain related to predominant trade winds, including the jet stream (Kara and Sahin, 2023) affects biodiversity and water availability (UN-WATER, 2019). The future hydrological demand for the Global South is not reflective of local realities. Changes in rainfall patterns have an impact on crops and productive conversions. In regions with lower rainfall, the temperature rises, irregular monsoon water evaporates, droughts increase, and a lack of water affects the growing demand, especially in metropolitan areas (Gao et al., 2022; Sarker, 2022).

According to the Drought Monitor in Mexico, on 31 May 2024, 57.88% of the country suffered from lack of water (CONAGUA, 2023). The study area of the metropolitan area of Cuernavaca, in the center of México, was greatly impacted by chaotic urbanization, economic activities, and deforestation. Later monsoons, poor water infrastructure, and insufficient sanitation put the government under increasing water stress availability and safe sanitation (Montero-Martínez et al., 2010; IMTA, 2011; Martínez-Austria and Patiño-Gómez, 2012; IPCC, 2024; INECC-SEMARNAT, 2018; UN-WATER, 2019; CONAGUA, 2021; INECC, 2021). The available data do not include an interdisciplinary assessment of water resources from local stakeholders and public administrators (Höllermann et al., 2009). The current national and regional public policy lacks an interdisciplinary socio-environmental development by prioritizing economic growth at the cost of chaotic urbanization (Delgado Ramos, 2019), ecosystem deterioration (Jaramillo et al., 2018), overexploitation of aquifers (Oswald, 2023), pollution of rivers, and irrigation channels (Valladares-Cisneros et al., 2021).

Confronted with these challenges, the present study addresses integrated water management, including complex socio-environmental interactions in worsening climate change scenarios in the center of Mexico. The research simulates with various climate models the water availability for different users in a drought-stressed region in the metropolitan area of Cuernavaca in the Center of Mexico, where complex socio-ecological activities affect the existing supply, demand, and hydrological balance. This study represents similar conditions in other countries in the Global South that are affected by climate change, population growth, chaotic urbanization, unsustainable ecosystems, and a lack of water management. The present research explores different climate change projections for rainfall variability with extreme droughts and floods in the study region.

Water availability in this metropolitan region depends on forest conservation in the Ravines System of Northwest Morelos (RSNM), which provides water for population, industrialization, service activities, and agriculture. Morelos, situated at a lower elevation near the coast, observed the region's highest monthly mean temperature in May (2024; 24.87°C) and the driest monthly mean precipitation in

February (2.07 mm). The Projected Anomalies by State for the period 2040–2059 (Ref. Period 1995–2014) under SSP3-7.0 (estimate) an increase in maximum annual temperature of 2.01°C, 28.5% of more summer days. There are 57.5% of tropical nights above 20°C. It has a steep slope of 3,000 meters that generates torrential downpours and drags sediments (World Bank Group, 2024).

The study investigates the development of a Water Evaluation and Planning (WEAP) model for precipitation, temperature rise, and annual aquifer recharge, incorporating socioeconomic factors and population growth. Interviews with key political and social authors examined the hydrological balance of water distribution among users, ecosystem requirements, and potential climate change impacts. The methodology selected the three best and most optimal Atmosphere–Ocean General Circulation Models (AOGCM) for the distribution of precipitation based on climate data (1970–2000). It established projections for AOGCM CNRM-ESM2, CNRM-CM6, and MIROC6, taking into account the long-term (2081–2100) simulation. The same database (WorldClim, 2024) processed SSP 370 and 585 for climate change scenarios. This study explores the future water balance of a regional dryland with potential climate change impacts, population growth, lack of clean water, and conflicts. The research examines an Integrated Water Resources Management (IWRM) approach in the RSNM, an exceptional biodiverse ecosystem (Jaramillo et al., 2018) with highly permeability of the basaltic rocks as the principal recharge of the aquifer in the growing metropolitan area of Cuernavaca for human and productive activities. The conclusion indicates that the current policy of water management is inadequate, affecting human water needs, industrial activities, services, agriculture, and biodiversity.

The legal framework, political priorities, environmental management, and climate change uncertainty (Taylor et al., 2008) establish the conditions for an analysis of the available water resources, the user demands, and the socio-environmental conditions. The predictive study contributes to informed decision-making, public planning, adaptation, and resilience-building to climate change impacts in a complex regional socioecological system for the short, medium, and long term.

1.1 Case study in the metropolitan area of Cuernavaca, Morelos

Mexico is highly exposed to multiple risks and vulnerability (World Economic Forum, 2024) because of two warming oceans, two mountain chains along the seas (Sierra Madre), and a transversal volcanic chain with semiarid and arid ecosystems that are increasingly impacted by drought (northwest, Pacific coast), floods in the southeast, and extreme weather events on both coasts. The projected scenarios for the 21st century predict an annual average temperature rise of 3.5°C by 2061–2090, roughly in the range of 1961–1990. The precipitation will decrease by at least 15% (Montero-Martínez et al., 2010; Gobierno del Estado de Morelos, 2014) related to changing trade winds. The RIOCCADAPT Report (Moreno et al., 2020) states that Mexico is experiencing the highest risks in Latin America with temperature increase, precipitation decrease, and extreme river flows. The costs for damages and losses are estimated to be US\$ 3,754 million. Oswald (2023) has warned for more than 20 years that climate change represents serious threats to Mexico, not only to more frequent and stronger hurricanes in coastal areas but also because of

TABLE 1 Historical groundwater availability in the Cuernavaca aquifer (own elaboration).

	Annual recharge average	Natural discharge compromises	Volume concessioned	Availability (Mm ³)
DOF 31-01-2003	No data	No data	No data	33
August 28, 2009 decree	395	175.2	198.49	21.31
Ha consultants 2010	No data	No data	184.7	3.1
CONAGUA 2010	344.2	125.1	199.1	20
DOF 20-12-2013	344.2	125.1	211.44	7.65
DOF 17-09-2020	344.2	125.1	199	20.1
REPDA 08-04-2023	344.2	125.1	200.75	18.35

*DOF: Diario Oficial de la Federación; REPDA: Registro Público de Derechos de Agua.

temperature rise and the alteration of the monsoon pattern with severe droughts and floods in the country (Oswald, 2016, 2023).

The UNAM Climate Change Research Program (PINCC) states that the average temperature rise in Mexico is about 1.69°C to 2°C, compared to the beginning of the 20th century (PINCC, 2024). This is higher than the global average (1.23°C). In 2023, the disastrous hurricane Otis in the Acapulco tourist resort generated the fourth highest annual cost of 16 billion dollars due to a 30°C higher sea water temperature (SwissRe, 2023). In 2024, Hurricane John produced in 5 days the annual precipitation affecting again Acapulco and 214 more municipalities. Climate change models also indicate precipitation changes, later monsoons, and higher temperatures. Rainfall distribution is extreme, with longer periods of drought and destructive floods (Estrada et al., 2023). CONAGUA forecasted five periods of extreme temperature in 2024 (CONAGUA, 2024). Climate change scenarios necessitate Mexico to improve its models for extreme events, thereby allowing preventive adaptation in the most vulnerable regions. Hotter climate scenarios include planning, learning-based approaches, and flexible solutions grounded on local data for building resilience to the predicted hydrological and climate changes (Pahl-Wostl, C., 2008).

The increasing impact of climate change creates uncertainty in humans and ecosystems (Jaramillo et al., 2018). High altitude and permeability in the RSNM on the northern Chichinautzin mountain chain recharges the aquifer, called the “Water Forest,” by dominant groundwater flows north–south and north-southwest (Pohle, 2006). As per official sources, the groundwater level in the aquifer is in equilibrium with some degree of overexploitation whenever multiple differences exist in the official data (Table 1)¹. The forest in the Ravines System of Northwest Morelos (RSNM) (Figure 1) is critical for biodiversity, surface water, and aquifer recharge for Cuernavaca’s metropolitan areas. The preservation of this RSNM forest is vulnerable to changes in land use, deforestation, bushfires, and population growth coupled with social marginalization. This region also includes small endorheic micro-watersheds characterized by their biotic, edaphologic, and geological characteristics (Jaramillo et al., 2018; Oswald, 2023).

¹ The present research indicates a tendency toward an equilibrium with slight aquifer overexploitation. The official data indicate availability of 33Mm³ (DOF, 2003); on August 28, 2009, 21.31Mm³; in 2013, 7.65Mm³. This discrepancy does not reflect the real availability of water in the Cuernavaca aquifer; reality could be worse than expected. No available data on aquifer extraction exists.

Multiple sources of domestic or industrial wastewater, agriculture, livestock activities, Urban Solid Waste (USW), and soil erosion can contaminate water before it can serve the population. Bendig (1985) analyzed the highly fractured basalt rocks using isotopic studies and the DRASTIC methods, establishing a high vulnerability to contamination in the Cuernavaca aquifer (Bendig, 1985). Her isotopic studies demonstrate that the main recharge comes from the north, corresponding to the Chichinautzin. Tritium concentrations suggest that groundwater age is young and does not exceed 42 years. The extraction by wells is concentrated in the megalopolis, generating some local sinking and altering the local flows toward the south. Since 2010, the average annual precipitation has been above 980 mm, and the study region is privileged with climate and water resources due to higher rainfall in this northern zone. During the dry season, the surface flows are reduced by 20–50% (CONAGUA, 2020). Climate change projections for the region simulate temperature rise and rainfall variability with extreme events (floods and droughts) that affect water quantity, exacerbate pollution, and deteriorate ecosystems (Gobierno del Estado de Morelos, 2014).

2 Methods

The three adequate AOGCM for the study region with the information from eight AOGCM of precipitation for SSP 370 and 585 were downloaded from the WorldClim portal (<https://www.worldclim.org>) between 1970 and 2000 and for the future of 2081–2100 to analyze climate change scenarios and future water demand for the study region. A system perspective integrates climate change uncertainty into simulations, and the simulations examine regional differences, anthropogenic processes, and potential conflicts among water users.

A possible modification of climate patterns could affect biodiversity and several crops, leading to a productive reconversion, especially sugar cane production. In regions that lack rainfall and experience rising temperatures, droughts may occur, leading to water evaporation (Gao et al., 2022; Sarker, 2022). Climate change scenarios identify future impacts of climate on local water resources. The IPCC (2024) presents reduced future climate projections from CMIP6 (Coupled Model Intercomparison Project), which, unlike CMIP5, integrates land use change and other socioeconomic data in addition to trajectories and forcing processes (O’Neill et al., 2016; WCRP, 2021). WorldClim processed 10 General Circulation Models (GCMs) for CMIP6: BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, GFDL-ESM4, IPSL-CM6A-LR, MIROC-ES2L,

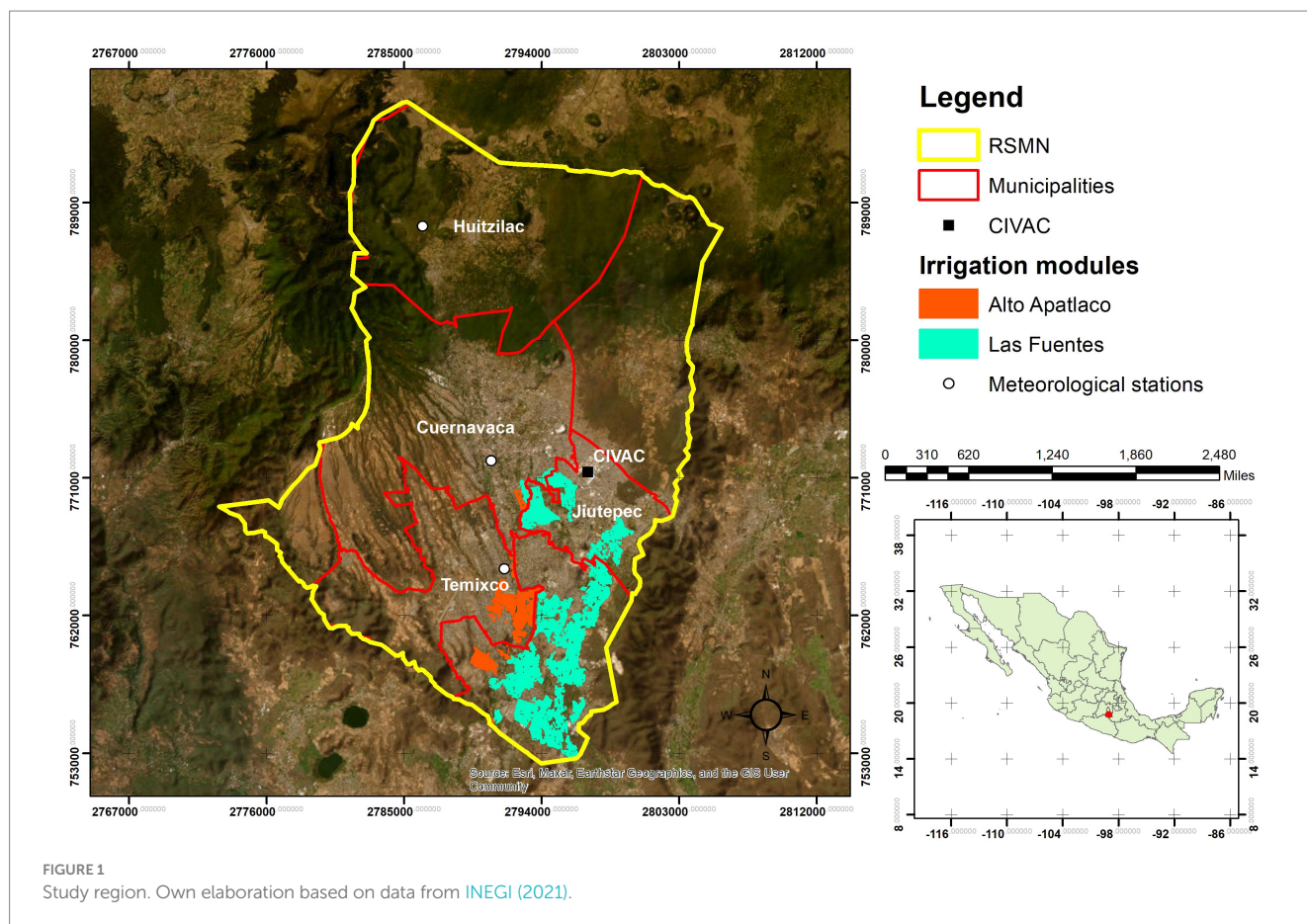


FIGURE 1
Study region. Own elaboration based on data from INEGI (2021).

MIROC6, MRI-ESM2, and for four SSPs²: 126, 245, 370, and 585 (Kikstra et al., 2022). Additionally, the Water Evaluation and Planning (WEAP) model, developed by the Stockholm Environment Institute (SEI), is a worldwide reference tool for decision-making based on Integrated Water Resources Management (IWRM). It operates under the principle of hydrological balance (Díaz and López, 2017). Salinas Villafañe and Paz Rada (2011) explains that this model provides a comprehensive range of factors that influence the management of water resources, including anthropogenic processes. Giraldo (2014) elucidates that the WEAP approach investigates climate change impact on water distribution among diverse users, including the ecosystem.

According to NOM-011-CONAGUA-2015, in Mexico, the difference between the total sum of inflows (recharge) and the total sum of outflows (discharge) represents the volume of water lost or for aquifer storage over an established period (CONAGUA, 2020). The

general balance equation, as per the law of conservation of mass, is as follows:

$$\text{Inflows (recharge)} - \text{Outflows (discharge)} = \text{change in aquifer storage}$$

Applying this equation to the aquifer study, the inputs are represented by the total recharge, the outputs by the total discharge, and the change in mass by the water storage:

$$\text{Total recharge} - \text{total discharge} = \text{change in aquifer storage}$$

Different complex socioecological systems (Binder et al., 2013) were framed within the Social-Ecological System (SES), including the interactions between social users and resource governance, based on agreed rules and limited by the natural system, where the existing resources and their units determine the resource availability (Ostrom, 2019).

Assessing the regional risk of extreme events (droughts, forest fires, cyclones, tropical storms, tidal surges, landslides, typhoons, sea level rise, etc.) and projected changes in baseline climate parameters (terrestrial temperature, atmospheric precipitation, and specific humidity) do not exist whenever they identify potential patterns of changes (CAF, 2014). Climate models are “a numerical representation of the climate system that is based on physical, chemical, and biological properties, including its components, their interactions, and

2 The SSP (Shared Socioeconomic Pathways) are scenarios of global socioeconomic change projected to 2100. They define different reference policies that occur with concerted international efforts addressing climate change beyond the already adopted measures by countries committed to the Paris Agreement. They also include multiple reference models related to underlying factors, such as population, technological, and economic growth, which could lead to highly different future emissions and temperature rises, even without any climate mitigation policy (Hausfather and Drake, 2018).

feedback processes, which explain some of its known properties.” Atmosphere–Ocean General Circulation Model (AOGCM) represents climate systems near the most complete end of the spectrum currently available, toward more complex models with interacting chemistry, social, and biological processes (Kikstra et al., 2022).

In the study region, climate change affects the biosphere and social systems with complex interactions (Calderón-Contreras and White, 2020), affecting multiple actors in economic and political activities (Sánchez-Santillán et al., 2015). Rathe (2017) suggests an interdisciplinary system methodology with complex, unpredictable, and nonlinear interrelated processes. This study examines a complex socio-ecological system analysis with interactions, dynamics, threats, and pressures at different levels (Collins et al., 2011). A hierarchical and multiscale approach promotes self-organization, which reduces vulnerability and increases resilience (Levin, 1988). The study also considers potential positive and negative impacts, including the global, national, and regional climate change impacts synthesized by the Intergovernmental Panel on Climate Change (Kikstra et al., 2022; IPCC, 2024).

The performance evaluation yielded the three best AOGCMs for the RSNM with estimated precipitation and temperature anomalies for the future climate, based on their effectiveness in modeling regional precipitation patterns. The performance of numerical variables is based on climate metrics and establishes the scope and limitations of the climate simulation in the study region by AOGCM scenarios. Cavazos et al. (2013) identified five validation climatic metrics to evaluate the performance of the AOGCM: the root mean square error (RMSE), mean absolute error (MAE), standard deviation (SD), and correlation coefficient (r). The sum of these variables gives an overall value, which should be close to 1 in order to get a good performance (see Supplementary Annexure 1).

Root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (D_{sim} - D_{obs})^2}{n}}$$

Where D_{sim} and D_{obs} represent the simulated and observed data, respectively, and n is the number of observations at each grid point. The root mean square error frequently measures the difference between the values (sample or population values) predicted and observed in an estimated model. It magnifies prediction errors in a single measure by comparing different models for particular data sets.

Mean absolute error (MAE):

$$MAE = \frac{1}{n} \sum_i^n |D_{sim} - D_{obs}|$$

The Mean Absolute Error (MAE) measures the disparity between two continuous variables, taking into account two sets of data (some calculated, some observed) relating to the same phenomenon. It is used to quantify the accuracy of the prediction techniques by comparing predicted versus observed values.

Standard deviation (SD):

$$SD = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n}}$$

Where X and Y represent the value of a variable at a given time and \bar{X} is the climatological average value.

Correlation coefficient:

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n (Y_i - \bar{Y})^2}}$$

Y represents the value of a variable at a given time, and X is the climatological average value from the WorldClim portal and analyzed for the eight AOGCM. GeoTiff files were processed by generating a raster cut that correspond to the study area. The correlation coefficient is a statistical measure that quantifies the strength and direction of a linear relationship between two variables. All of these statistical metrics underscore the choice of the selected AOGCM for the study area. The performance analysis selected from the eight AOGCM was the SSP 370 and 585 scenarios for the base climate (1970–2000) and the perspective (2081–2100) in RSNM. In addition, a formula was devised to attain the identical weighted average of these five standards (Table 2). The ranked analysis for precipitation and the eight AOGCMs evaluated for RSNM in Table 2 have values close to 1. The three AOGCMs used were CNRM-ESM2 (France), CNRM-CM6 (France), and MIROC6 (Japan) because they were the best evaluated for the region. The last column indicates the weighted average value of the five metrics applied to each AOGCM analyzed for precipitation (Supplementary Annexure 1 includes the calculations of the two performance analyses of the eight AOGCM).

This research analyzes SSP 3 (fragmentation) and SSP 5 (fossil fuel-based development), both dominant socioeconomic trends in Mexico and the study region. SSP3 with forcing level 70 represents substantial land use changes (especially global forest cover) and high greenhouse gas (GHG) emissions. It combines societal vulnerability (SSP3) with comparatively high forces. An SSP 5 with a high forcing level is the only SSP emission scenario for a radiative forcing of 8.5 Watts/m² in 2100. The selection of models, scenarios, and horizons for this analysis visualized scenarios reflecting a fossil fuel-driven development with low adaptation and a high level of GHG emissions, without any additional efforts to limit CO₂-equivalent emissions exceeding 1,000 ppm by the year 2100. This radiative forcing may increase the global surface temperature from 2.6°C to 4.8°C (Kikstra et al., 2022). These two SSPs were chosen to visualize the most adverse scenarios linked to the current national policy (O'Neill et al., 2016).

TABLE 2 Databases used (own elaboration).

Databases used in this research
Cartographic information, digital elevation model, location of wells, aquifer boundaries (according to decrees), maps of type and land use, territorial planning, socioeconomic data, ecological flow, Kc, and infrastructure
Precipitation and maximum temperature distribution from WorldClim version 2.1 climate data and future climate projections (www.worldclim.org).
Basic cartography of Morelos (state and municipal boundaries) (INEGI)
Surface and groundwater availability
Databases of meteorological stations and hydrometric stations (BANDAS-CONAGUA)
Vulnerability and climate change studies

See Supplementary Annexure 2 for more information.

The precipitation anomalies scenarios analyzed using the WEAP model and WorldClim Coupled Model Intercomparison Project 6 (CMIP6) databases incorporate greenhouse gas emissions scenarios (SSP) to establish the performance analysis. The WorldClim version 2.1 (WorldClim, 2024) and the reduced climate projections from CMIP6 at a spatial resolution (expressed in min of a degree of longitude and latitude) of 2.5 min could result in some errors in capturing local variability, especially in the rocky study region. CONAGUA conducted the meteorological stations 17047 (Huitzilac), 17004 (Cuernavaca-DGE), and 17014 (Temixco) as the most representative for the upper, middle, and lower parts of the RSNM.

Figure 2 shows the methodology outline. The precipitation anomalies were obtained by subtracting the historical climate (1970–2000) from the data projected in the scenarios. The climate change scenarios provide the precipitation anomalies that feed the WEAP model. These climate change scenarios simulate precipitation anomalies, which feed the WEAP model with a Geographic Information System based on a graphical interface for water resources planning and hydrological balances for participatory planning. It incorporates an IWRM approach and generates impact models for climate change scenario anomalies. By linking supply and demand, WEAP integrates hydrological processes at the basin scale and allows regional water balances. Scenarios encompass demand, supply, precipitation, elevation, hydraulic sections, runoff, vegetation cover, infiltration, evapotranspiration, interaction between surface and groundwater, water quality, and projections of climate change scenarios with socioeconomic aspects (Sánchez Torres et al., 2006). Hydrologic balance is based on the law of conservation of mass, in which the total input of water (referring to precipitation and inflows) must be equal to the total output (evapotranspiration, withdrawals, and runoff) plus the net variation in accumulated storage, territory data (type of soils, land use, data from hydrometric stations, kc, ecological flow, etc.), and socioeconomic conditions (infrastructure, population growth, monthly

variations of waste, users, reuse, demand, and deforestation) (Arreguín-Cortés et al., 2015). The WEAP model for the RSNM was developed by a GIS map defining the main watercourses, demand sites, water flows, wastewater treatment plants, ecological flow, the aquifer, and the general study area dynamics. Information was complemented by maps, documents, governmental studies, and scientific articles (Table 3 and Supplementary Annexure 2).

The study examined water use demands for the base year, population, water consumption, water reuse, monthly variations in consumption, losses in the distribution system, and other data were included. The RSNM water system was mapped for the components of the water table depth, hydrological parameters, land use, topographic and geomorphic features, crop data, soil properties, metrology/climatology, irrigation, yields, water demand, demographic details, water transmission and availability of both surface and groundwater, abstraction nodes, supplies, outflows, demand sites, infiltration/runoff links, together with other data from the WEAP model for the study area (see Supplementary Annexure 2).

The perimeter is the boundary of the Cuernavaca aquifer, considering the natural boundaries and its hydrological position. The total outflow comprises an update based on the groundwater REPDA (Registro Público de Derechos de Agua-CONAGUA) of pumping extractions (REPDA-CONAGUA, 2019). Horizontal outflows consist of discharges from the aquifer to a surface stream, which contribute to ecosystem conservation. Flows calculated rainfall and runoff for the Soil Conservation Service (SCS), developed by the U.S. government agency (Sánchez Torres, 2016) (see Supplementary Annexure 3). The available water quality data (BOD5, COD, and TSS) were recorded in the return flows of the demand centers, wastewater treatment plants, and rivers. The main wastewater treatment plants for the study area were included with their percentage of removal of pollutants and efficiency. The data corresponding to the Cuernavaca aquifer was also verified for the storage capacity, recharge, interaction with other

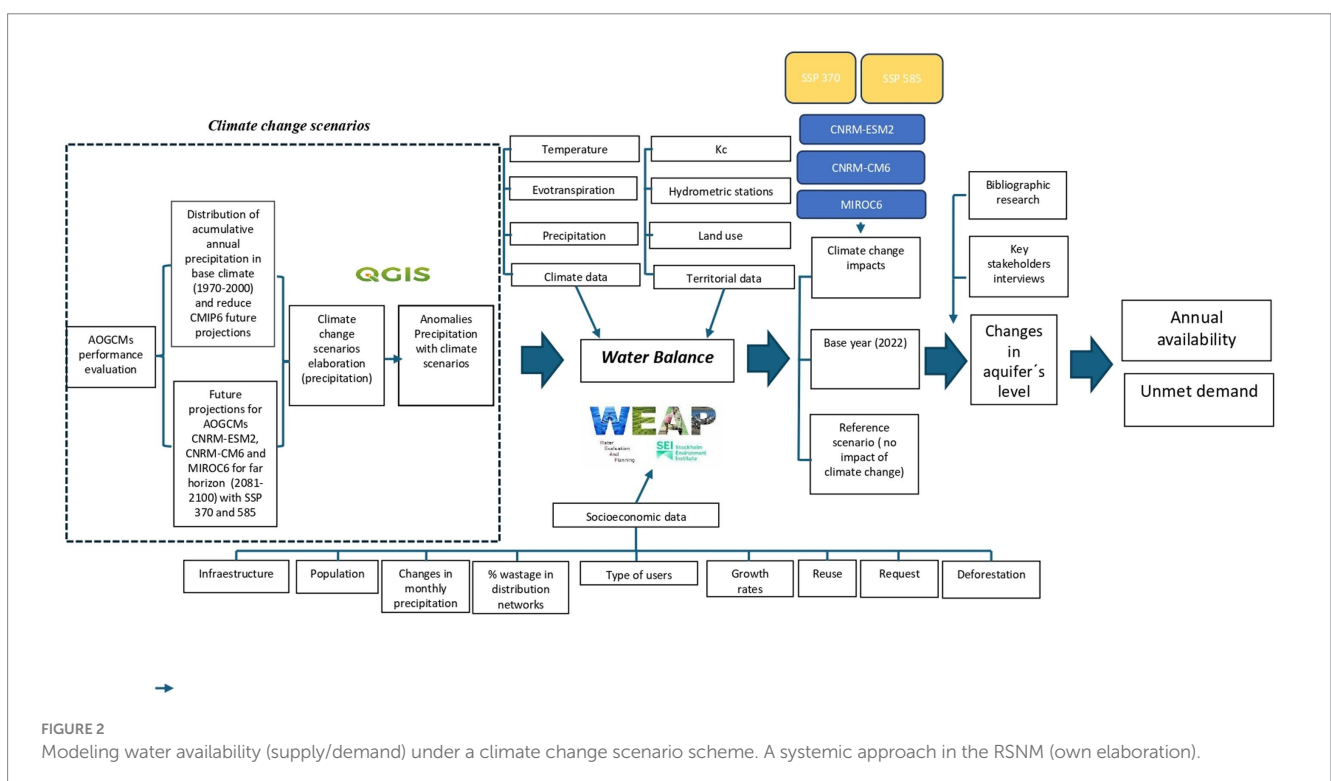


FIGURE 2 Modeling water availability (supply/demand) under a climate change scenario scheme. A systemic approach in the RSNM (own elaboration).

TABLE 3 Performance evaluation of eight AOGCM for SSP 370 and SSP 570 for precipitation in 2081–2100 (own elaboration).

AOGCM indicator	RMSE	MAE	SD	Coef. Correlation	Global value
SSP 370					
CNRM-CM6-1	14.0920	7.4167	88.5479	0.9909	1.0930
BCC-CSM2-MR	33.2102	17.9167	91.5458	0.9389	1.0738
CNRM-ESM2-1	13.5777	8.6250	86.4153	0.9890	1.0606
MIROC6	19.0706	10.7083	71.7444	0.9851	0.8430
IPSL-CM6A-LR	25.0948	15.4167	71.5289	0.9600	0.8153
MIROC-ES2L	26.9227	13.8333	71.1643	0.9588	0.8113
MRI-ESM2-0	31.5463	16.0000	69.1622	0.9395	0.7677
CanESM5	35.7025	19.3333	65.9968	0.9266	0.7075
SSP 585					
CNRM-CM6-1	22.6440	13.2500	92.7563	0.9766	1.0413
CNRM-ESM2-1	20.2443	12.1667	90.3295	0.9780	1.0292
MIROC6	21.9678	12.2500	75.1907	0.9696	0.9203
MIROC-ES2L	31.4947	18.2500	71.2870	0.9393	0.8654
MRI-ESM2-0	37.9945	19.9167	70.6055	0.8996	0.8412
CanESM5	34.6663	19.4167	67.6083	0.9323	0.8329
IPSL-CM6A-LR	34.7910	19.7500	66.9475	0.9258	0.8259
BCC-CSM2-MR	43.3513	25.8333	63.2053	0.8784	0.7687

aquifers, ecological flows, and infiltration zones for the scenarios from 2023 to 2100.

The WEAP model structure consisted of the development of (1) the base year (2022), (2) the reference scenario with no climate change impact for the period 2023–2100, (3) the SSP 370 climate change scenarios for the three AOGCMs chosen in the performance analysis for the period 2081–2100, and (4) the SSP 585 climate change scenarios for the three chosen AOGCMs in the performance analysis for 2081–2100. This WEAP model calculates the water balance for each node by linking distinct time scenarios. A node represents a physical component, such as a demand site, treatment plant, aquifer, or location along the Apatlaco River (the main tributary in the RSNM). The nodes were linked by lines representing natural or human-made processes, such as rivers, diversions, and return flows. All water entering the system at any given time is stored in the soil, aquifer, river, tributary, reservoir, or exits the system (Supplementary Annexure 4). Finally, the constructed WEAP model was calibrated by calculating the values of the indicators Nash-Sutcliffe Efficiency NSE, Percent Bias, PBIAS, Root Mean Squared Error to the Standard Deviation, RSR, and Ratio Simulated vs. Observed Flow Standard Deviation, SDR, utilizing the simulated and real flow values for the Apatlaco River, provided by the hydrometric station B18271 Temixco of CONAGUA (Sánchez Torres, 2016) (Supplementary Annexure 5). Thirty interviews with key actors in the study area provided qualitative data for the interpretation of climate change impacts for the study area, mentioning existing conflicts and trends of the ongoing anthropogenic processes.

3 Results

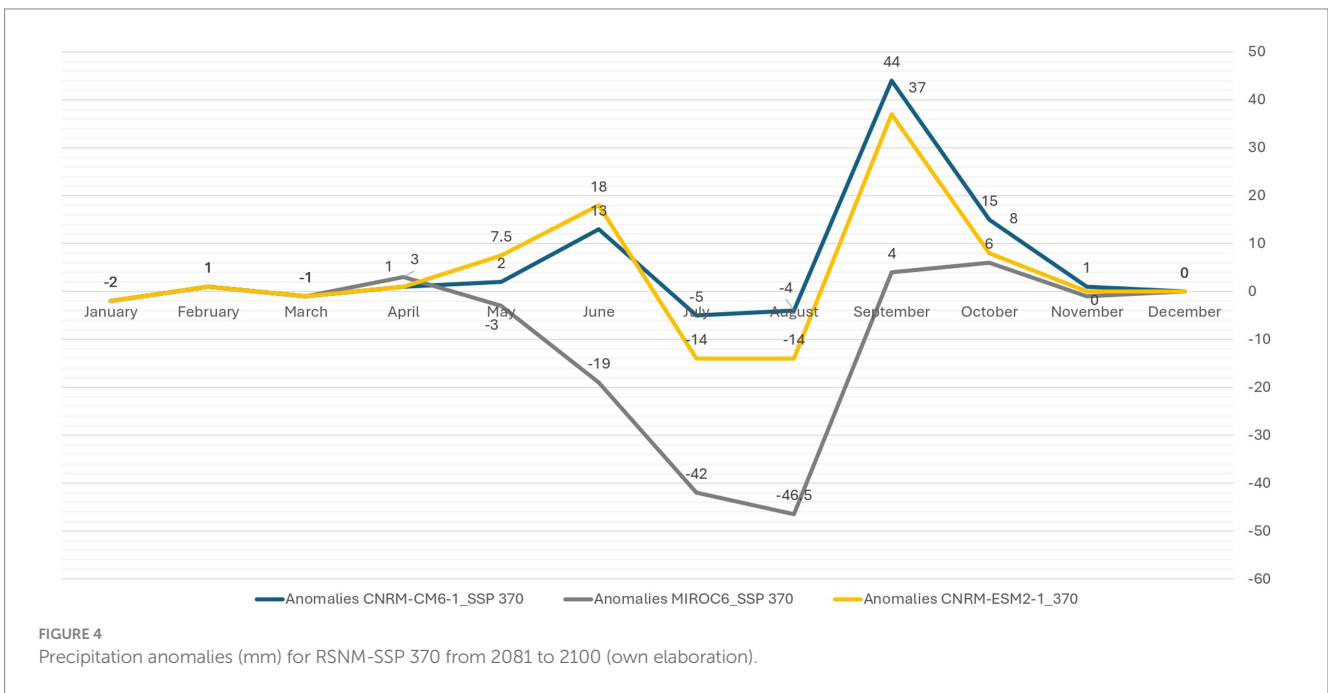
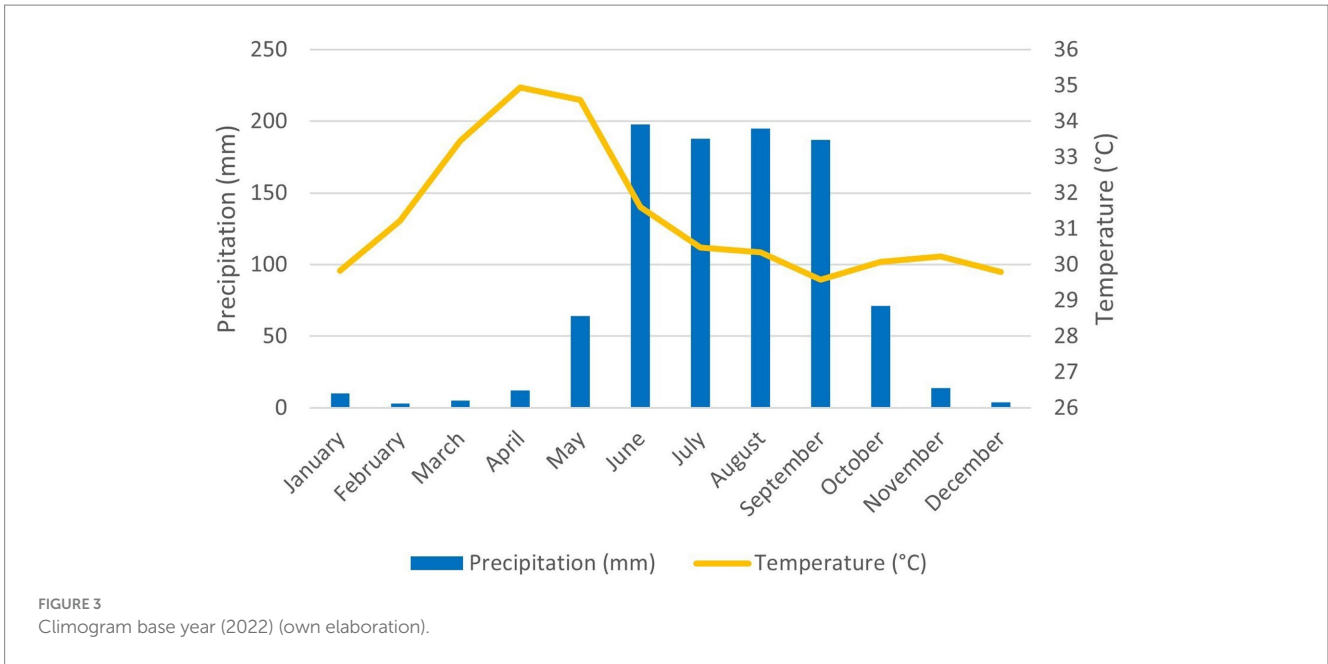
The three meteorological stations (17047-Huitzilac, 17004-Cuernavaca DGE, and 17014-Temixco) operated by CONAGUA for the metropolitan area indicate the most significant

rainfall during June and September (Figure 3) in 2022. In 2024, the delay in the monsoon was until July (CONAGUA, 2024).

Figure 4 shows the distribution of cumulative annual precipitation and its anomalies in the climate base 2022 and the total precipitation projections for the three selected AOGCM in 2081–2100 by SSP 370 (fragmentation). These scenarios indicate a significant decrease in precipitation, especially for AOGCM MIROC6, with a loss of up to 46.5 mm during August. There are also summers with less rainfall, atypical rainfall, and severe drought periods. The monsoon season commences later in all of the simulation models. Traditionally, in August, there is an interstitial drought, which is necessary for the development of the corncob, the basic food in the region (Ibarra Sánchez et al., 2020). The lack of water and delay in the monsoon affect the entire crop cycle (Estrada et al., 2023), threatening especially the poor farmers in rainfed agriculture, forcing them to migrate (Oswald, 2023).

Figure 5 shows the cumulative annual precipitation, its anomalies, and the AOGCMs for 2081–2100 and SSP 585 (fossil fuel-based development) precipitation projections. The AOGCM model for SSP 585 predicts a significant decrease in precipitation from June to September, atypical rainfall in June, and prolonged periods of drought with higher temperatures. Similar data was observed in the case of SSP 370. MIROC6 indicates the highest decrease of 59 mm in July, specifying a shift of the rainy months toward September and October. MIROC6 is composed of three sub-models: atmosphere, land, and sea ice-ocean. It has improved accuracy in simulating natural climate variability and a better response to climate change representation of ocean-atmosphere interaction. It has also improved fidelity in simulating extreme events in extreme pathways for catastrophic scenarios (Tatebe et al., 2019).

Figure 6 shows the precipitation anomalies for scenarios with SSP 370 and 585 in the study area. The SSP 370 model projects higher anomalies, whereas the AOGCM MIROC6 indicates the highest

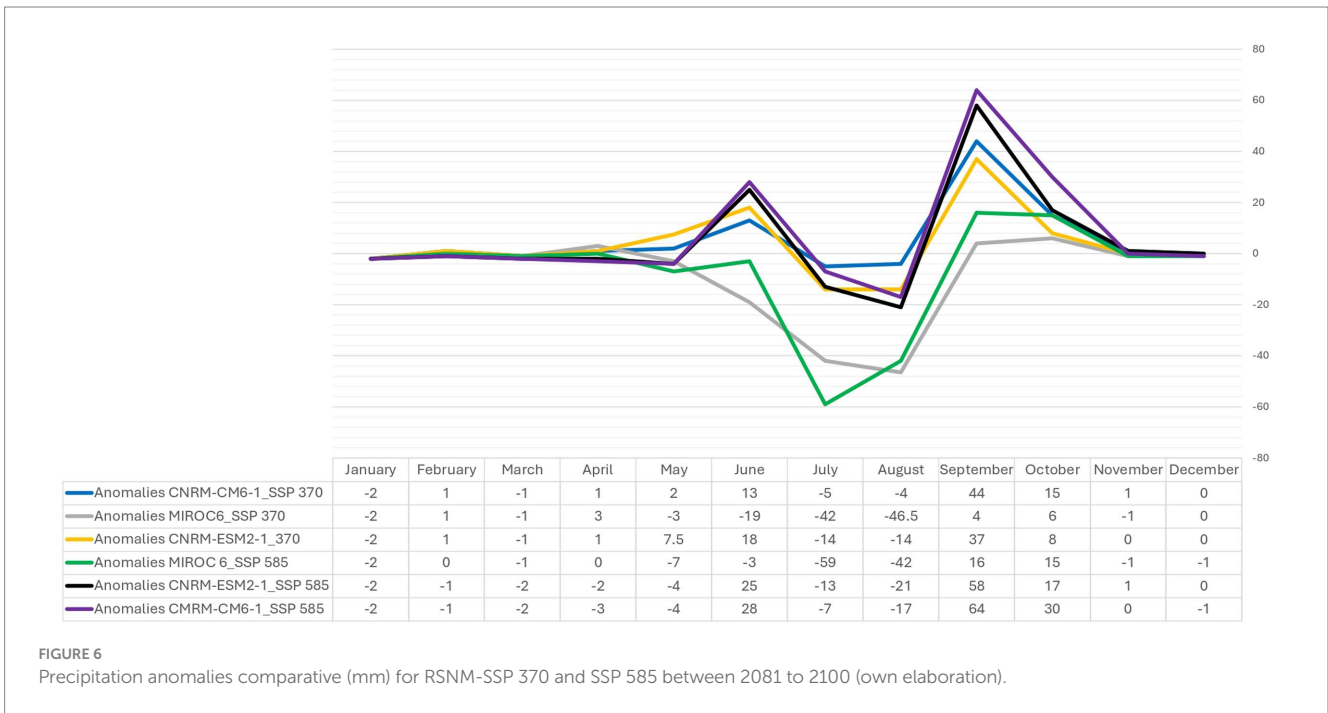
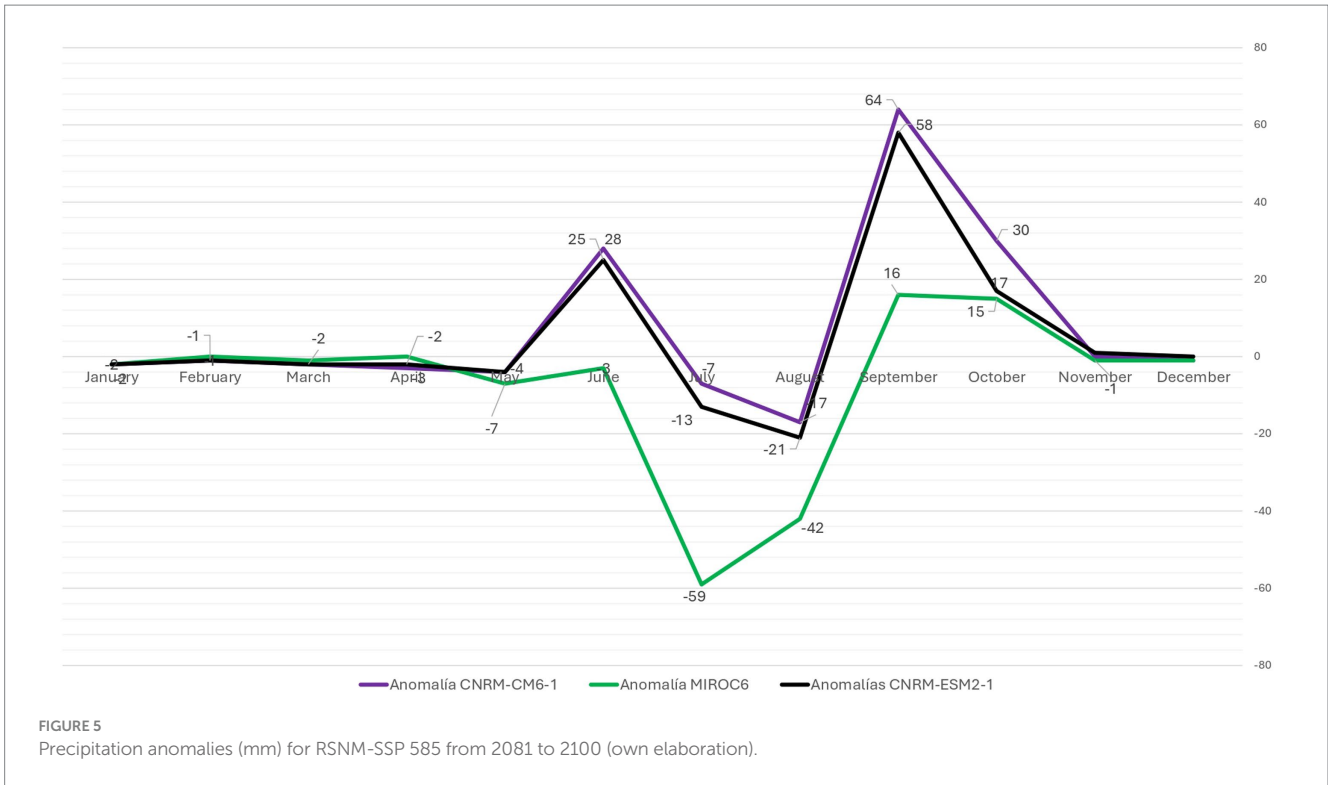


decrease in precipitation related to massive fossil use. Both SSP projects simulate a displacement and a later start to the monsoon season with atypical rainfall up to October. The transition from fossil energy to renewable energy and water forest recovery could improve water availability and improve regional climate conditions with lower temperatures. SSP 585 (intensive hydrocarbon use) simulates a longer drought period with less rainfall, whereas SSP 370 indicates greater rainfall.

The reference data on recharge and extraction published by CONAGUA, 2020 identifies a total annual recharge of 344 Mm³ for the Cuernavaca aquifer (CONAGUA, 2020). The highest recharge occurs during the rainy months (June–September). The reference scenario (2023–2100) and the comparison of natural recharge

indicate a tendency to decrease in most of the models, from 344 Mm³ (reference scenario) to 323 Mm³ for SSP 370 and AOGCM MIROC6 (Figure 7).

The estimated water demand of 197 Mm³ in the study area is mainly extracted from the aquifer, where the cities of Cuernavaca and Jiutepec have the highest water requirement (Figure 8). The irrigation module Las Fuentes derives the majority of its water from the aquifer, in contrast to the Alto Apatlaco irrigation module, which relies on surface water. Furthermore, there are water leaks in the distribution networks. In the base year (2022), the aquifer supply requirement for the City of Cuernavaca was estimated at 120 Mm³, and it is projected to exceed 200 Mm³ by 2100. The Las Fuentes irrigation module also has a significant aquifer requirement of more than 60 Mm³ compared to



the Alto Apatlaco irrigation module, predominantly supplied by surface water.

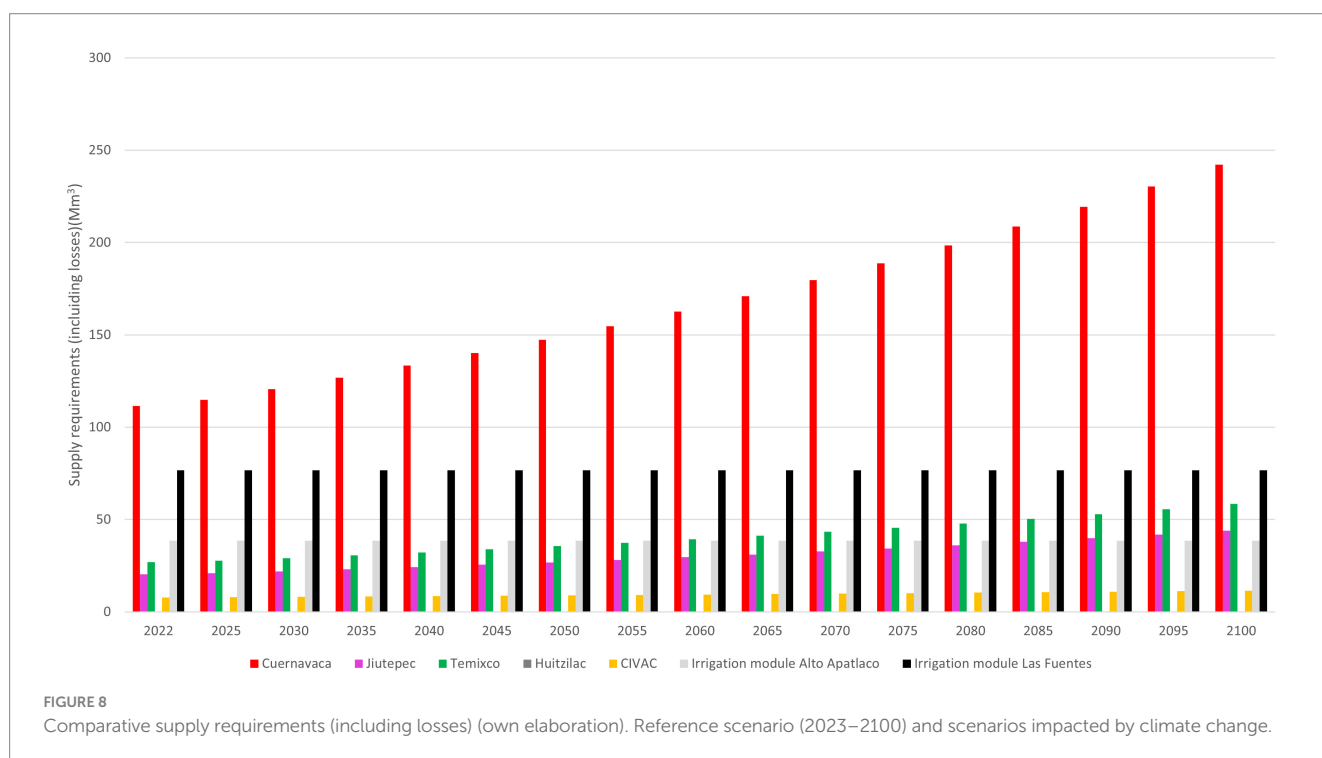
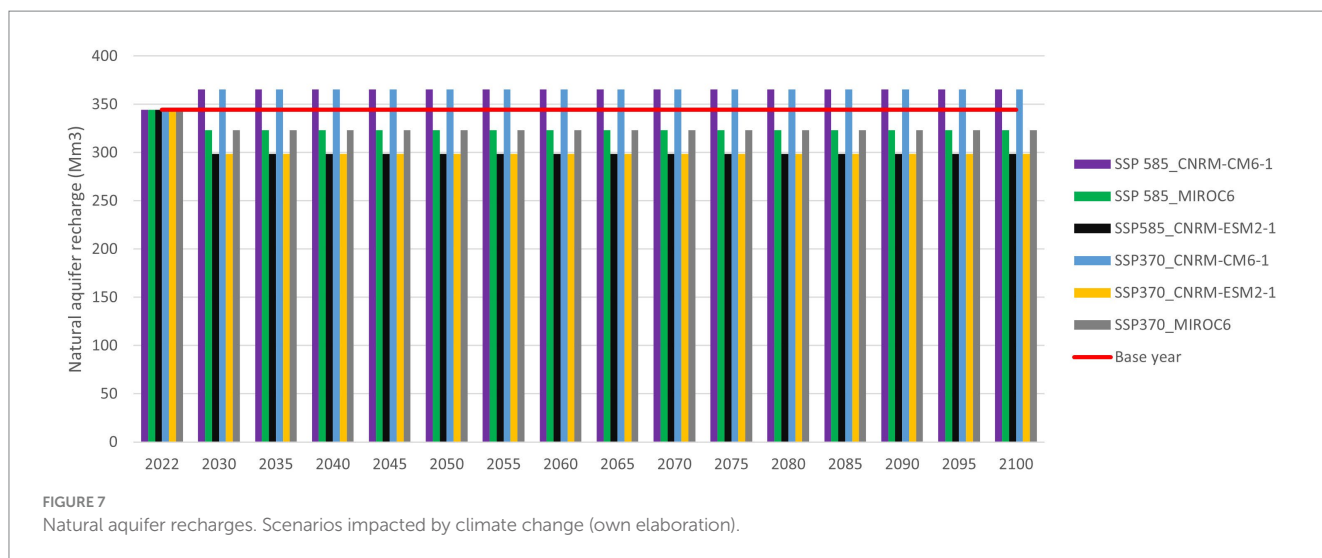
Figure 9 shows a tendency to increase supply requirements under change scenarios conditions to more than 500 Mm³ in 2090 in the study region.

Figure 10 shows the hydrological balance and annual aquifer availability with an approximate yearly average availability of 20 Mm³ for 2022 with a decreasing equilibrium from 2032. In 2024, the

population did multiple protest marches of lack of water because the official data of piezometry date at least two decades ago.

Figure 11 shows SSPs and AOGCM indicating a significant decrease in the average annual availability of the aquifer of 20 Mm³ for 2022 and a decreasing tendency for almost all scenarios. The worst scenario was MIROC6, with SSP 585 missing 1,500 Mm³ in 2099.

Figure 12 shows the unmet demand resulting from the WEAP model for the study area. A similar shortage is observed in the first

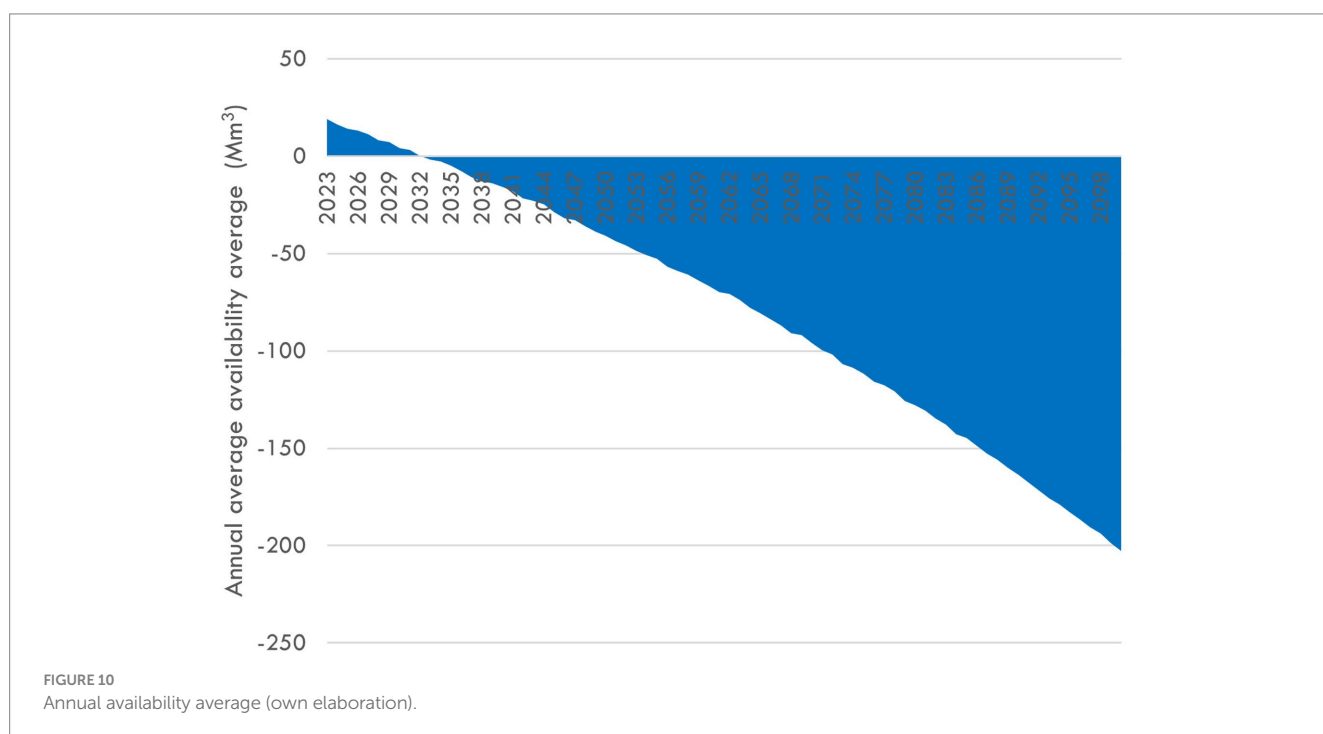
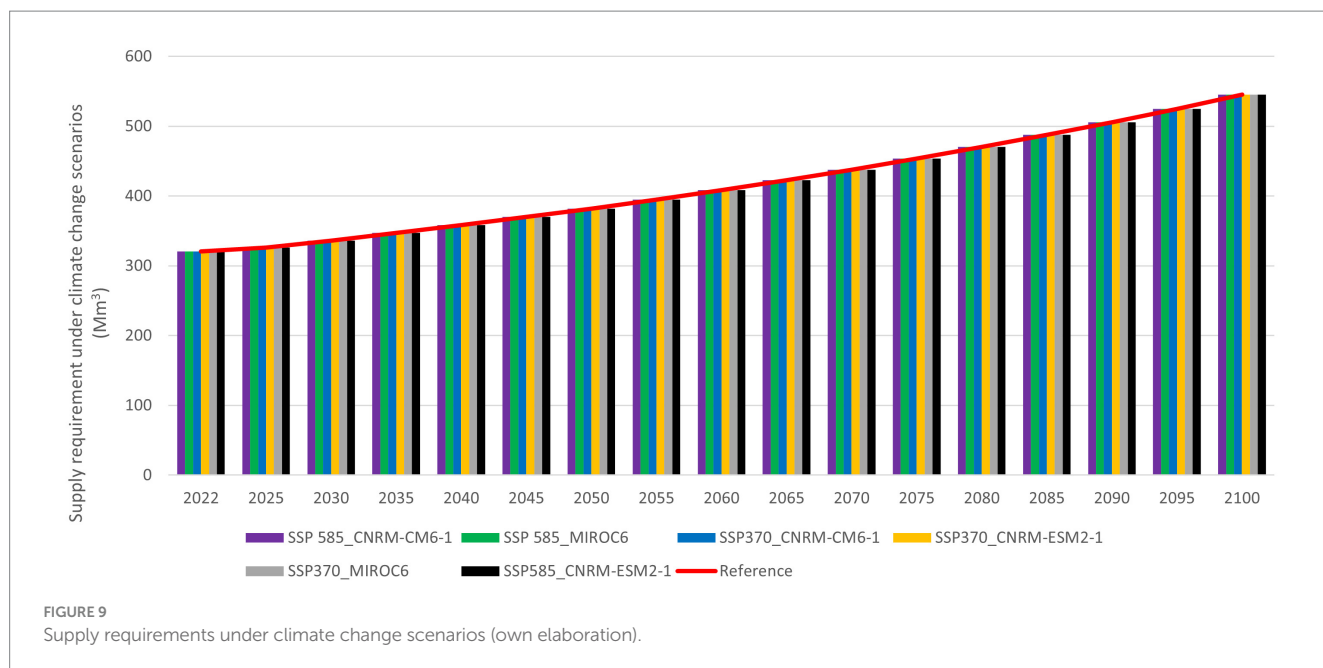


place for the irrigation module. Las Fuentes is the most vulnerable, as it depends on the recharge of springs. Similarly, the industrial city of CIVAC is committed from 2045 and the City of Cuernavaca by 2070.

4 Discussion

Observing the distribution of accumulated annual precipitation in 2022 and the accumulated precipitation projections in the three AOGCM obtained for both SSPs indicates that the regional water demand is increasing as a result of population growth, economic activities, food demands, higher temperatures, less rainfall, delays in the monsoon, and extreme weather events. In 2022, the region

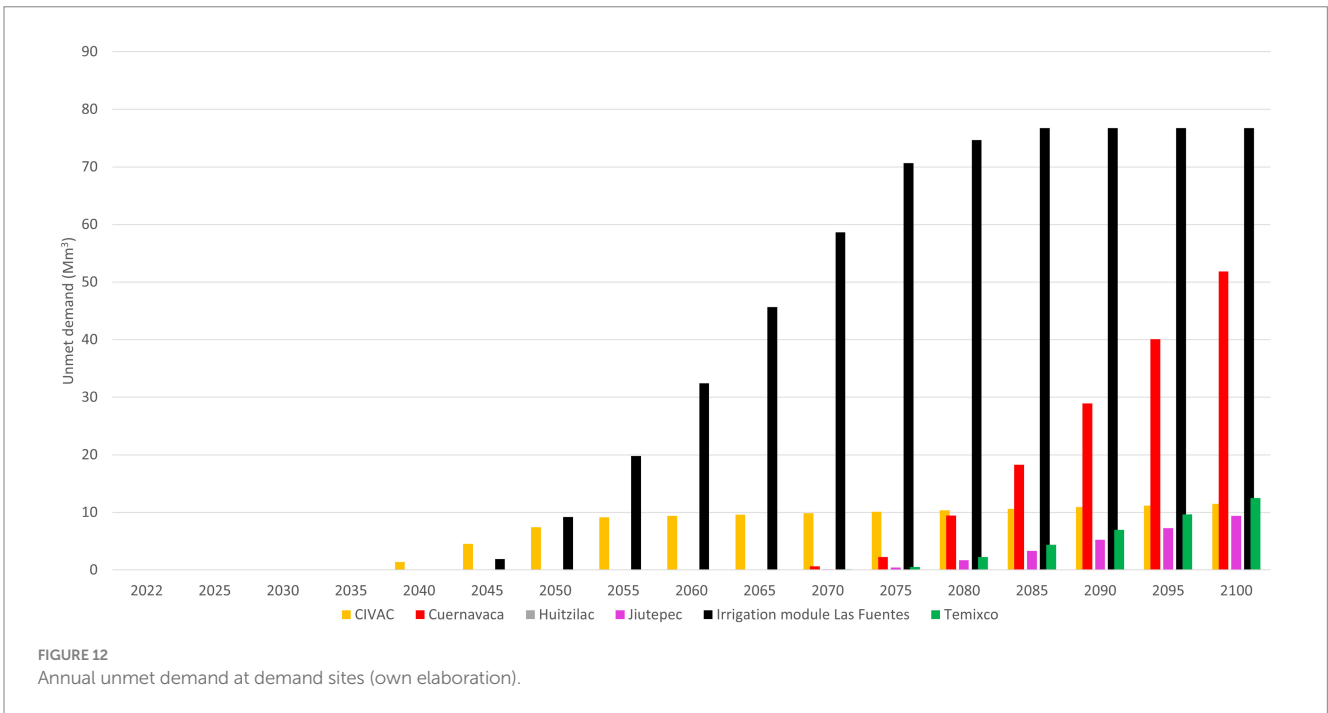
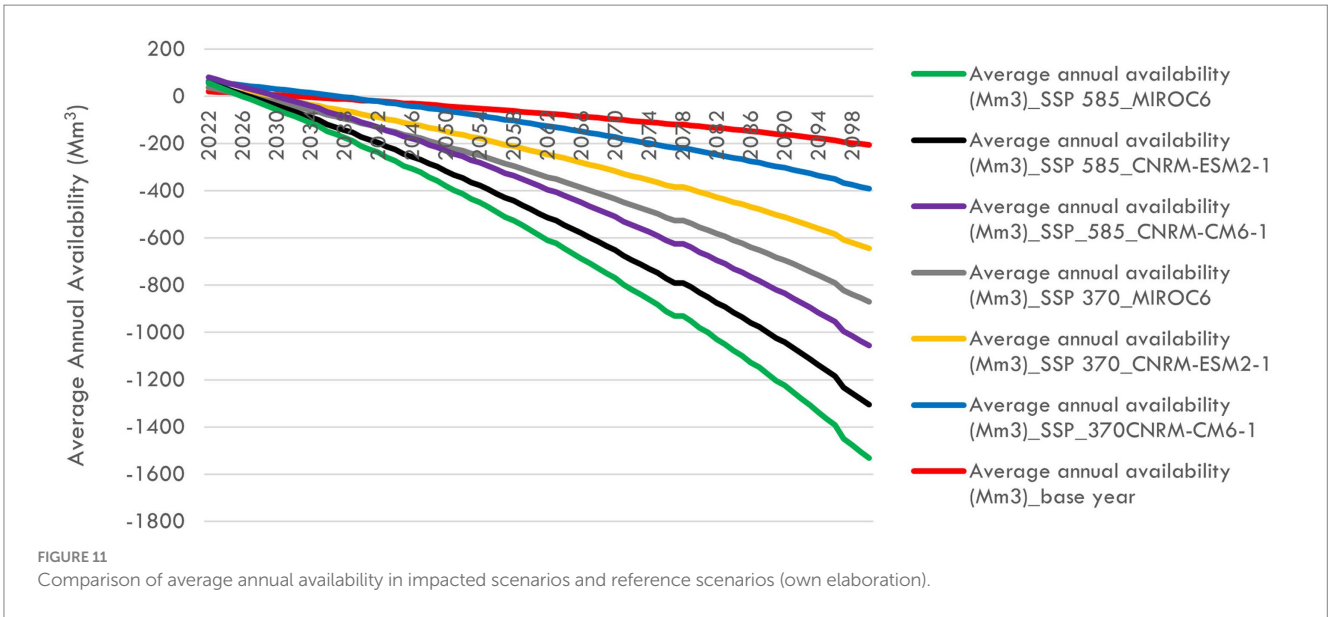
demanded about 197 Mm³, mainly extracted from the metropolitan aquifer. The irrigation module in Las Fuentes experiences the highest demand from the regional aquifer and is the first affected by a deficiency in groundwater, to produce ornamental plants and party gardens. The cities of Cuernavaca, Jiutepec, and the entire metropolitan area are threatened to run out of drinking water supplies without an alternative management of the water forest and an energy transition. The irrigation module of the Alto Apatlaco is mainly supplied with surface water from the mountain. Therefore, a collective effort of peasants and local and state authorities is required to protect the natural protected area, conduct systematic reforestation with local plants, combat bushfires, and establish a technical irrigation system to provide subsistence food from corn, beans, and vegetables.



According to the WEAP model, the demand for water increases during the hot months of March to May, later June or July with higher temperatures, evapotranspiration, and less rainfall. Furthermore, the regional water supply in the metropolitan area is over 40 years old, has been broken by earthquakes, and nearly half of the water has been lost in the distribution networks. A projected increase in water demand of 242 Mm³ for Cuernavaca, coupled with a high population growth rate, is projected by the year 2100. The metropolitan area of Cuernavaca may expand to the Yautepec-Cuatla metropolis and the different aquifer, indicating a significant population growth from 378, 476 inhabitants in 2020 to 445, 848 inhabitants in 2032 (INEGI, 2020;

Gobierno de Morelos-Hacienda, 2023). An adverse climate change scenario may increase the monthly demand by more than 20 Mm³ during the dry season and later monsoon.

In the historical climate scenario, the monsoon commenced from June to September with about 980 mm of annual rainfall. All of the AOGCMs indicate a significant decrease in precipitation (less severe with SSP 370), atypical rain, and longer periods of drought in SSP 585 (referring to conventional fossil fuel-based development with major mitigation challenges). MIROC6 simulates a severe drop of -59 mm for July in 2098, while the monsoon moves to September and October with much higher temperatures during the dry



months. CNRM-CM6_SSP 585 also illustrates a decrease in rainfall with anomalies of -17 mm in August, 64 mm in September, and 30 mm in October in the long-term scenario. The largest lack of precipitation occurred in MIROC6 SSP 370 (assuming high population growth and low economic development with low levels of education in the local society) with anomalies of up to -59 mm in July. Both of these SSP models assume less rainfall, atypical rainfall, extreme events, and longer severe drought periods. The WEAP model for the study region demonstrates a negative trend in the metropolitan aquifer's natural recharge, with significantly higher demand and unmet demands between -200 and $-1,500$ Mm^3 .

These climate impacts also impact the historical flow of the Apatlaco River and the existing springs in the mountain, and the water quality in terms of BOD5, COD, and TSS deteriorate with lack of water and higher temperatures, worse during the dry season. The WEAP model coincides with official sources of the hydrological balance with an annual availability of the aquifer of approximately 20 Mm^3 per year in 2022 (CONAGUA, 2020). In 2020, the same source published data for recharge and extraction with an annual natural recharge of 344 Mm^3 in the metropolitan aquifer, where the rainy season contributed from June to September. The AOGCM, MIROC 6_SSP 370, observes the greatest tendency to decrease the natural aquifer recharge, with a decrease from the reference year of

344 Mm³ to 323 Mm³ in MIROC6_SSP 370. The hydrological balance also expresses the unmet demand for the irrigation module Las Fuentes in 2024, as well as the city of Cuernavaca, which is highly affected by climate change scenarios. Water shortages occurred in 2022 between April and May in Cuernavaca and during the same months in 2024. By 2061, significant water shortages are projected for Cuernavaca, reaching approximately 18 Mm³ by 2086.

A trend toward overexploitation of the Cuernavaca aquifer exists today with a discrepancy of official data. If current extraction rates and trends continue, it would not be feasible to satisfy the demands to satisfy the needs of the region with the unmet demand in the WEAP model for the study area. The modification of climate patterns affects several crops, leading to a productive reconversion from corn, sugar cane, and sorghum, reducing the local subsistence food. The most vulnerable areas are the southern and southeastern regions of Morelos. These trends confirm the climate change models developed by Estrada et al. (2023), which predict that climate change has altered and delayed the distribution of precipitation during the annual rainy seasons.

Morelos in the Face of Climate Change, Ortíz et al. (2013) analyze the climate series of the state with a trend toward an increasing air temperature, more hot days (Tx >35°C), and maximum temperatures above the 90th percentile. This increase is noticeable from 1990 on in all climate zones of the state, which is highly evident in the semi-hot and hot zones in the center and south of Morelos, where the temperature increased in May 2024 up to 47°C in Tlaquiltenango, Morelos (CONAGUA, 2024). Regarding precipitation, Bolongaro-Crevenna et al. (2013) demonstrate the variability of rainfall regimes in Morelos with a delay at the beginning of the monsoon. These authors analyze the water availability in the Cuernavaca aquifer with the recorded trends of groundwater extraction, producing overexploitation of the aquifer in 4.7 years starting in 2011. They use a Spatial Distributed Analysis (SDA) to perform a pixel-by-pixel water balance model, considering temperature, precipitation, EVT, vegetation, land use, edaphology, and geology. Precipitation reached 4,781 Mm³; 64% was lost by EVT, 24% generated virgin runoff, and 12% recharged the aquifer. This analysis reported a deficit in water availability in the Cuernavaca aquifer of -133.34 Mm³ since 2013. Thus, studies on groundwater dynamics are necessary, such as the simulations with SWAT (Soil and Water Assessment Tool) and MODFLOW (distributed hydrogeological model) software (Arnold et al., 1993) or piezometric or isotopic studies (Bendig, 1985).

Specific risks for the water supply in Morelos are related to the changes of 73% in biodiversity and 97% in forest cover, agriculture, and livestock, according to the Study of Vulnerability and Adaptation to the Effects of Climate Change prepared by the National Autonomous University of Mexico in its Climate Atlas (UNAM, 2022). Despite this knowledge being public, the actions of the state and municipal governments are limited and poorly articulated. The existing bias in official water data represents interests and power relations with public information manipulation, where bottled water suppliers, irrigated agriculture, real estate, ornamental fisheries, industries, and growing cities are pressuring for more water. At the state level, alternative sources and greater efficiency in the use and reuse of treated water should complete the missing and disperse water supply data by the irrigation module Las Fuentes, the industrial zone CIVAC, and the metropolitan area of Cuernavaca and Jiutepec. Greater adaptation to growing water shortage implies searching for efficiency in agricultural and industrial

activities, policies to recover springs, aquifer recharge with treated water, conservation of natural areas, capture of rainfall water, energy transition technologies, and reforestation of the water forest. Sufficient water in quantity and quality allows economic development in the region, grants people living standards, and the SDG 6 to water and safe sanitation.

Processing hydrological data and forecasting climate change obliges a system approach to understanding the multiple interrelated factors affecting water supply, use, and pollution. Methodologically, evaluating water availability in the region with climate change scenarios should promote better data collection. Further, multiple extreme events oblige the development at the municipal level of the Atlas of Risk and train vulnerable people with increasing adaptation and resilience to upcoming extreme events. The Water Forest in the RSNM represents great potential to supply the water necessary for the development of Morelos. Its conservation in the upper watershed represents the hydric factory (Yu et al., 2022) for the whole region (Jaramillo et al., 2018). The surrounding mountains of the metropolitan area with greater precipitation and high permeability of basaltic rocks can recharge the aquifer. The semi-dry conditions of Morelos, changes in the monsoon, higher temperature, extreme climatic events, and less water availability represent similar conditions in multiple countries of the Global South and the reflections can serve as a case study for these regions.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/[Supplementary material](#).

Author contributions

JG-Z: Writing – original draft, Writing – review & editing. ÚO-S: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frwa.2024.1466380/full#supplementary-material>

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