



Integrating climate models to confront the illusion of certainty in water planning: evidence from Morocco

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Received: 24 September 2024 / Accepted: 29 December 2025
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Abstract

Stationary assumptions have shaped Morocco's national water planning for decades, fostering a perception of climatic certainty that has repeatedly failed during recent water crises. This article examines the implications of hydroclimatic non-stationarity on water planning in a semi-arid Moroccan basin. An ensemble of CMIP6 projections under SSP4.5 and SSP8.5 scenarios was statistically downscaled to drive a calibrated hydrological model, generating future streamflow projections that were integrated into a scenario-based water system simulation framework. The analysis incorporates competing municipal and irrigation demands, existing reservoirs, and seawater desalination contributions. Results reveal a general decline in future inflows, and significant inter-model divergence. Under these conditions, stationary planning assumptions systematically overestimate water availability and conceal critical system vulnerabilities. While reservoir-based supply alone cannot reliably meet future demands, desalination improves municipal reliability, but irrigation deficits remain severe across most plausible scenarios. In practice, adaptation options are constrained by existing infrastructure and governance realities. However, by combining a non-stationary climate framework with stakeholder-defined planning scenarios, the proposed approach enabled optimization of desalination design capacity to reflect both hydroclimatic uncertainty and water managers' priorities. Beyond physical constraints, the findings reveal the limitations of deterministic planning and a governance trap in which uncertainty is inadequately translated into action, as witnessed by repeated revisions of national water strategies, delays in commissioning of key infrastructure, and a tendency toward short-term, reactive crisis management rather than anticipated planning. The study emphasizes the urgent need for climate-informed, adaptive water planning that explicitly accounts for uncertainty and non-stationarity, particularly in water-stressed regions.

Keywords Hydroclimatic non-stationarity · CMIP6 projections · Hydrological modeling · Water system simulation · Adaptive water management · Water resources planning

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1 Introduction

Climate change is already challenging water security and raising fundamental questions about how water infrastructure is planned and designed under deep uncertainty (IPCC 2022). Historically, the planning and design of water infrastructure projects have relied heavily on hydroclimatic stationarity, where hydrological systems are considered to fluctuate within a time-invariant statistical envelope (Milly et al. 2008). Until around 2010, most water resource planning in Europe was based on stationary assumptions (Machado et al. 2015; Prosdocimi et al. 2015). Many regions of Asia and Africa follow a comparable pattern, which has shaped how reservoirs, flood management systems, water transfer projects, and irrigation schemes are planned and designed (Wilson et al. 2017; PNE 2020; Zbigniew and Licznar 2021). In the United States, agencies such as the USGS have based critical infrastructure design, including dam sizing, reservoir capacity, and flood control systems, on long-term observed hydrological records (England et al. 2018; Ryberg et al. 2024). Limited data availability, computational constraints, and institutional path dependency have historically been used to justify stationary approaches. However, such approaches provide limited insight into the potential impacts of climate change on water resources management (Ray and Brown 2015).

As concerns about stationarity increased, the need to incorporate climate uncertainty into water planning has been strongly emphasized by international institutions and the scientific community (Milly et al. 2008; Ray and Brown 2015; IPCC 2022). Recent efforts have tested the integration of expanded hydroclimatic information, including stochastic modeling and General Circulation Model (GCM) projections to account for a wider range of plausible future climatic conditions (Bureau of Reclamation 2007, European Commission 2007; 2009a, Brekke et al. 2009; England et al. 2018).

By incorporating these projections into water planning, water managers can better assess the significance of climate risks (Fletcher et al. 2019; Casey et al. 2020). The starting point is the use of GCM projections, which can be fed into hydrological models to simulate future streamflow, and subsequently into water system models to assess system performance and management policies (Brown et al. 2020). This chain of modeling provides estimates of potential future climate and water supply conditions, offering a framework for decision-makers to test long-term objectives that can be achieved under a wide range of plausible futures. Crucially, such an approach moves planning beyond the outdated stationary paradigm (Giuntoli et al. 2015).

Although Morocco, like many countries in Africa, bears no historical responsibility for global warming, it is not immune to its negative effects and is, in fact, among the countries most vulnerable to climate impacts. Morocco and its regional counterparts are expected to face major challenges, including an increase in extreme weather events such as heat waves, droughts and floods (Fontaine et al. 2013; Tanarhte et al. 2015; Filahi et al. 2016; Giannaros et al. 2019; Grant et al. 2025). These impacts have already been observed to affect water systems and ecosystem structure, exacerbate water scarcity, and threaten food production. Such changes have led to a decline in Morocco's Gross Domestic Product (GDP) and have impeded its economic growth.

To face these challenges, Morocco has launched, during the last two decades, many water projects and strategies. However, despite the broad scientific consensus on hydroclimatic non-stationarity (Milly et al. 2008), large-scale water infrastructure projects continue to be

designed based on a stationary paradigm (National Water Strategy 2009; Water Transfer Project 2009; 2023; PDAIRE 2010, 2020). In fact, hydrologic modeling, reservoir operation simulations and environmental impact assessments for all ongoing and planned water systems continue to rely on stationary observed data (DRPE 2017, 2017, EIE Rhiss 2017; EIE Dar Maimoun et Bou Ahmed 2019c; EIE Ayacha 2019a; EIE Kheng Grou 2020; EIE Beni Mansour 2019b). Within this framework, national and regional water authorities implicitly assume that future hydroclimatic patterns will resemble those of the past. This assumption creates an illusion of certainty about future climatic conditions.

To illustrate the challenges of water planning in Morocco under the stationary paradigm, and the advantages of incorporating GCM projections, we selected a Mediterranean basin as a testbed. Belonging to a region recognized as one of the most climate sensitive areas globally (López-Moreno et al. 2014; Essa et al. 2023; Tejedor et al. 2024), the basin is already under significant stress and relies on a diversified mix of surface water, groundwater, and desalination to meet different demands. This combination of scarce resources, competing demands, climatic exposure, and institutional constraints makes it an emblematic case of the challenges confronting water planning in semi-arid regions under deep hydroclimatic uncertainty.

2 Study area and current water resources management

2.1 Basin of interest and climatic conditions

The basin of interest is located in northern Morocco and comprises two semi-arid sub-basins (Fig. 1A): Rhiss and Nekkour, with a total area of $\sim 1370 \text{ km}^2$. The main river network extends over 178 km, originating from the Rif Mountains, characterized by complex geological structures. Elevation ranges from 268 m in the southeast to 1971 m in the northwest. The hydrologic regime is ephemeral to intermittent, with rivers flowing over impermeable to semi-impermeable geological formations, except along the coast, where permeable depos-

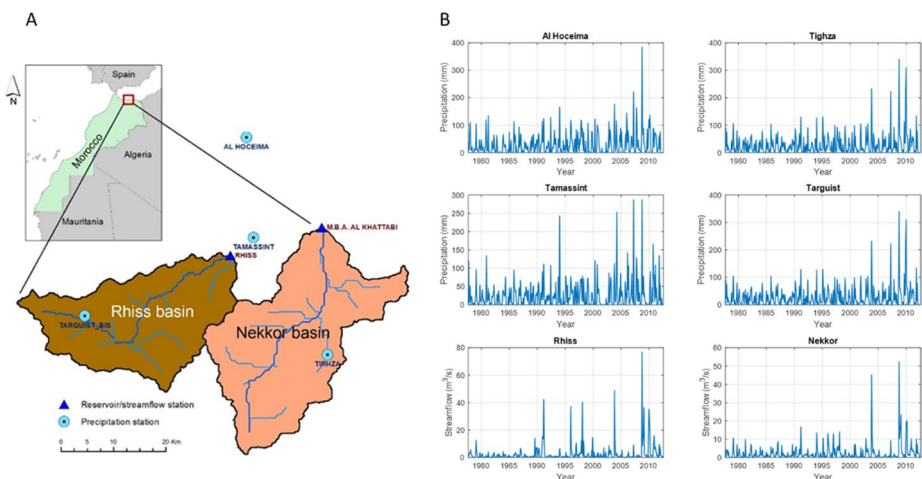


Fig. 1 Location of the Rhiss and Nekkour basins (panel A) and precipitation time series for the Rhiss-Nekkour basin and upstream dam inflows (panel B)

its host the Nekkour alluvial aquifer. The region's climate is Mediterranean with increasing semi-arid characteristics toward the interior. Annual precipitation averages 360 mm, mostly falling during the wet season (September–May), with 60% to 80% occurring between November and March.

The analysis of observed precipitation and the streamflow reveal pronounced interannual variability (Fig. 1B). This variability contributes to rapid runoff during the wet season. The region's exposure to the sea in the north and the highlands in the south increases its sensitivity to climatic influences from both the continent and the sea (Hakam et al. 2025).

2.2 Current situation of water resource management

The water system of the Rhiss-Nekkour was designed under stationary assumptions and formally guided by the National Water Strategy (SNE 2009), the National Water Plan PNE (PNE 2015 and 2020) and the Master Plan for the Integrated Development of Water Resources-LoukkosPDAIREL (2023), which frame Morocco's long-term water policy. The Al Hoceima region hosts three large dams, Rhiss (93 Mm³, under construction), Sidi Mohammed Ben Abdelkarim El Khattabi (SMBK, 33.6 Mm³), and Joumouaa (5.2 Mm³), with a combined storage of 131.8 Mm³. All these reservoirs are owned by the state and managed by the Hydraulic Basin Agency of the Loukkos.

Sedimentation has critically impaired the SMBK reservoir, built in 1981 for flood control, drinking and irrigation water supply (EIE Rhiss 2017). With an infilling rate of ~ 1 Mm³/y, its storage has fallen below the critical threshold, threatening the short- and medium-term reliability of supply. Delays in the completion of the Rhiss dam have constrained system's capacity to meet short-term municipal water demand (MWD), while irrigation supplies have faced severe deficits, forcing their suspension (DRPE 2017; PNE 2020).

Currently, the region's MWS relies on a seawater desalination plant and a monoblock desalination unit with a combined production capacity of 7.3 Mm³/yr, supplemented by around 3 Mm³/yr from groundwater resources (DIAEA 2017; ONEE 2020). While awaiting the Rhiss dam's potential commissioning between 2025 and 2030, the water balance shows that the system is unable to meet demand, with projected deficits reaching up to 26% for MWS and 100% for irrigation (DRPE 2016; EIE Rhiss 2017).

Given the severe sedimentation of SMBK and the limited capacity of Joumouaa, the analysis focuses on the Rhiss reservoir as the dominant future control on system reliability.

3 Data and water system assumptions

3.1 Instrumental records and reservoir system data

According to the World Meteorological Organization guidelines, at least 30 years of observed data are required for climatic analysis (Burroughs 2003). Such long-time records are often lacking in the MENA region, particularly Morocco, which limits consistent climate assessment. We collected the most continuous, consistent, and reliable long-term monthly time series of precipitation, temperature, and streamflow observations from the Directorate of Water Resources Planning (DRPE 2024).

Missing values were reconstructed using machine-learning techniques (ML), where we verified several conditions across the stations, including correlation ($r > 0.7$), homogeneity, consistency (common time window), stationarity of relationships and spatial proximity (< 30 km). After assembling all complete and incomplete time series, we divided the data into training and testing sets, ensuring that periods containing missing observations were excluded from the training phase.

The ML model was trained using the complete datasets and then applied to estimate missing values. Predictions were compared with unknown observations to assess model performance. Once validated, the model outputs were used to fill the missing values, which were subsequently reviewed to ensure internal consistency before being incorporated into further hydrological analyses.

Core datasets for modeling the water system were compiled to support the river-reservoir simulation model, including dam characteristics (e.g., crest elevation, outlet capacity, intake levels), reservoir level-surface area-storage capacity relationship, water demands, operation rules (e.g., release policies and supply priorities), and evaporation rates.

3.2 Water planning assumptions

Two approaches were used to evaluate the water management strategy adopted by decision-makers:

- (1) using observed hydroclimatic data as a proxy for future conditions (the *Stationary System Paradigm*), and
- (2) using projected scenarios from GCMs (the *System Projection Paradigm*).

The first approach forms the basis for the current water management strategy of the region (SNE 2009, EIE 2017; EIE 2020; ONEE 2020; Benchbani et al. 2022), where observed hydroclimatic data are incorporated into hydrologic and water resource models to inform system design. In contrast, the System Projection Paradigm accounts for climate-driven shifts in the mean, variance and extremes of hydroclimatic variables (Fig. 2), enabling the exploration of multiple plausible futures based on GCM projections, rather than relying solely on observed time series.

Concerning future water demands, MWD is estimated based population growth, household connection rates to the distribution network, per-capita allocations, consumption patterns, network efficiency, distribution requirements, etc. Irrigation demand is projected from

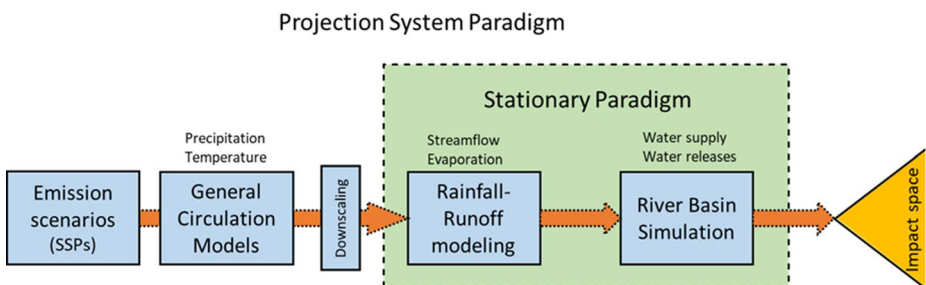


Fig. 2 Flowchart highlighting the adopted approach for stationary and projection system paradigms

irrigated area expansion, crop water requirements, irrigation efficiency, and related factors. Official projections in Morocco are provided by the National Office of Water and Electricity (ONEE) and the Ministry of Agriculture.

3.3 General circulation models projections

We used precipitation and temperature projections from the Coupled Model Intercomparison Project phase 6 (CMIP6). These time series were retrieved from the open-source portal provided by the World Climate Research Programme-WCRP (<https://esgf-node.llnl.gov/projects/esgf-llnl/>; accessed 2023).

We selected ten GCMs: CanESM5, CNRM-CM6, FGOALS-f3-L, FIO-ESM-2-0, GISS-E2-1-G, HadGEM3, INM-CM4-8, MIROC-ES2L, MRI-ESM2-0, NorESM2-LM, to obtain precipitation and temperature time series for the Rhiss and Nekkour basins over the period 1950–2100. Table 1 summarizes the CMIP6 models used in this study. The selected models were forced under two future greenhouse-gas emission scenarios: SSP4.5 and SSP8.5.

Although CMIP6 spatial resolution (~ 100 – 180 km) is coarse ($\sim 1,370$ km²), it remains consistent with the standard resolution of global climate models provided by the WCRP, where grid sizes typically range from 100 to 500 km (Risley and Zammit 2023). At such spatial resolutions, GCMs generally cannot reliably represent climatic features below ~ 200 km (Meehl and Stocker 2007). Despite this limitation, CMIP6 outputs have been widely and effectively applied, following appropriate statistical downscaling in hydrological impact studies for basins of comparable size (Beck et al. 2016; Seker and Gumus 2022; Risley and Zammit 2023).

While high-resolution regional climate modeling provides finer spatial detail and is generally better suited for local-scale climate analyses (Scaife et al. 2011; Jung et al. 2012; Demory et al. 2014; Benedict et al. 2019), it was not feasible in our case due to its substantial computational and data requirements. We therefore adopted statistically downscaled GCM outputs as a validated alternative.

Table 1 Summary of the GCMs used in this study

Model Abbreviation	Full Name	Institution & Country
CanESM5	Canadian Earth System Model v5	Canadian Centre for Climate Modelling & Analysis, Canada
CNRMCM6	CNRMCM61 (MétéoFrance/CLIMAT1)	CNRM, MétéoFrance/CNRS, France
FGOALSf3L	Flexible Global Ocean–Atmosphere–Land System Model – FV version 3	Chinese Academy of Sciences (FIO/CAS), China
FIOESM20	FIO Earth System Model version 2.0	First Institute of Oceanography (FIO), CAS, China
GISSE21G	GISS Model E2, version 2.1 – G	NASA Goddard Institute for Space Studies, USA
HadGEM3	Hadley Centre Global Environment Model v3	UK Met Office Hadley Centre, UK
INMCM48	Institute of Numerical Mathematics Climate Model v4.8	Institute of Numerical Mathematics (INM), Russia
MIROCES2L	Model for Interdisciplinary Research on Climate – Earth System v2L	MIROC, University of Tokyo/NIES, Japan
MRIESM20	Meteorological Research Institute Earth System Model 2.0	MRI, Japan Meteorological Agency, Japan
NorESM2LM	Norwegian Earth System Model v2	Norwegian Climate Centre, Norway

To correct biases in historical GCM simulations and adjust for their coarse spatial resolution, we applied three statistical downscaling methods: (1) Power Transform (PT), (2) Linear Scaling (LS) and (3) Quantile-Mapping (Qmap). Unlike dynamical downscaling, statistical approaches are more flexible and computationally efficient (Wilby and Wigley 1997; Benestad 2011), and adjust GCM time series to more closely match the observed data (Maraun et al. 2010).

4 Hydrologic and water system modeling

4.1 Hydrologic model Description

To assess the potential impacts of climate change on the Rhiss-Nekkor hydrology, we translated downscaled climatic projections into streamflow projections using a hydrologic model. Since 2016, we have developed and refined a multilayer feedforward neural network (MFFNN) model to simulate hydrologic responses across similar watersheds in Morocco (Zemzami and Benaabidate 2016; Zemzami 2015).

The MFFNN model was trained using the Levenberg-Marquardt algorithm with 36 consecutive years of streamflow, temperature and precipitation data to capture the nonlinear relationship between these variables (Fig. 3). This algorithm is an improved version of backpropagation that combines gradient descent with the Gauss-Newton method (Zemzami 2015).

The first 25 years of data were used for model training, the following 6 years for validation, and the final 5 years for independent testing with unseen data.

Because no universal methodology exists for determining the optimal ANN architecture, both network architecture and input selection in this study were optimized through a trial-and-error process (Zemzami 2015). Model performance was evaluated using three metrics: Root Mean Square Error (RMSE), the Nash-Sutcliffe coefficient (NSC) (Nash and Sutcliffe

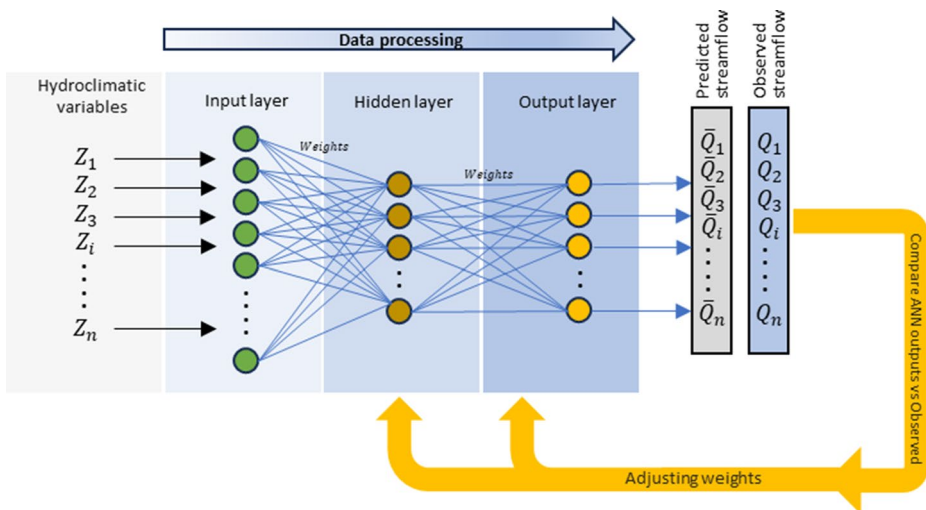


Fig. 3 Architecture of multilayer feedforward neural networks hydrologic model

1970) and the Persistence Index (PI) (Kitanidis and Bras 1980). The following equations describe these performance metrics:

The Root Mean Squared:

$$RMSE = \left[\frac{\sum_1^n (Q_i - \bar{Q}_i)^2}{n} \right]^{1/2}$$

The Nash-Sutcliffe coefficient:

$$C_{NS} = 1 - \frac{\sum_1^n (Q_i - \bar{Q}_i)^2}{\sum_1^n (Q_i - \bar{Q}_m)^2}$$

The persistence index:

$$C_{IP} = 1 - \frac{\sum_1^n (Q_i - \bar{Q}_i)^2}{\sum_1^n (\bar{Q}_i - Q_{i-1})^2}$$

Where Q_i is observed streamflow, $\bar{Q}_i$ simulated streamflow, Q_m average streamflow and n the number of data elements.

RMSE is used for peak flow evaluation and complete assessment of the model error, Nash-Sutcliffe for overall performance and goodness of fit, and Persistence Index is used to check the prediction lag effect (Zemzami and Benaabidate 2016).

4.2 Water system model

To anticipate water dynamics and distribution within a water system over the operational lifetime of planned infrastructure projects, water planners rely on a range of analytical tools and datasets. Among the most widely used tools today are water system models and water balance calculations, which help evaluate the performance of proposed infrastructure.

In this context, we developed a water system model for the Rhiss-Nekkor system to assess planning strategies and availability of water within the system. Figure 4 illustrates the conceptual model of the Rhiss-Nekkor, including variable inflows (VIF), confluences (C), reservoirs, water demands (IRR and MWD), groundwater (GW), irrigation return flow (IRF) and system terminal point.

Irrigation return flow represents the excess of water from irrigation that is not used by plants and therefore infiltrates to recharge groundwater. Based on the Environmental and Socioeconomic Impact Study of the Rhiss Dam (EIE Rhiss 2017), IRF was evaluated at 10% of the total irrigation water supplied.

This water system model is based on solving the following equation:

$$\Delta V = VE - VS - EN \times S \times 10^{-6}$$

Where:

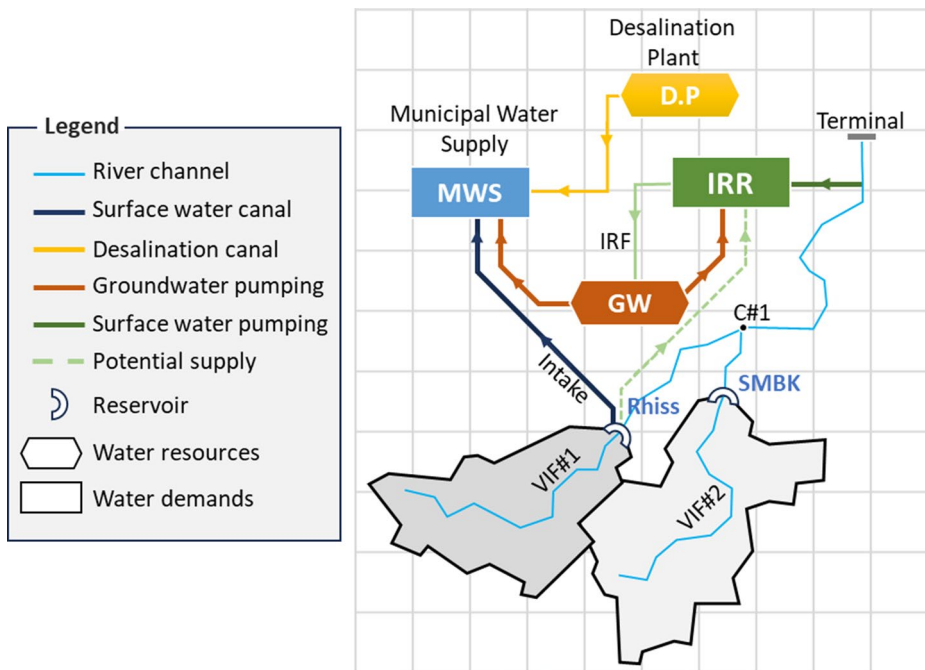


Fig. 4 Conceptual model of the Rhiss-Nekkor water system

ΔV : reservoir stock change in Million Cubic Meter (Mm^3)

VE : Volume of natural inflow at the reservoir site in Mm^3

VS : Volume of releases from the reservoir in Mm^3

EN : Net evaporation rate (in millimeters, mm)

S : Average surface area of the reservoir (in square kilometers, km^2)

5 Results

5.1 Stationary water planning

To address growing water demands and recurrent severe droughts, decision-makers relied on observed hydroclimatic time series (1977–2012) to plan the Rhiss reservoir (2024–2060) and the associated desalination plant (SNE 2009, EIE Rhiss 2017; ONEE 2020). While this may seem counterintuitive given the growing evidence of climate change and its impacts, this stationary approach to planning remains common practice in many African countries (Brekke et al. 2009; SNE 2009; EWS 2017; SSE 2019; PNE 2020; PNAEPI 2020).

First, we simulated the Rhiss reservoir under stationary conditions to meet MWD ($15 \text{ Mm}^3/\text{yr}$) and irrigation ($8 \text{ Mm}^3/\text{yr}$) water demands, considering only active storage (the volume between dead storage and spillway). The main results are presented in Fig. 5. Under these conditions, we tested operational scenarios assuming no climate-change-induced shifts in hydrologic variability. Simulation analysis revealed that the Rhiss reservoir can meet

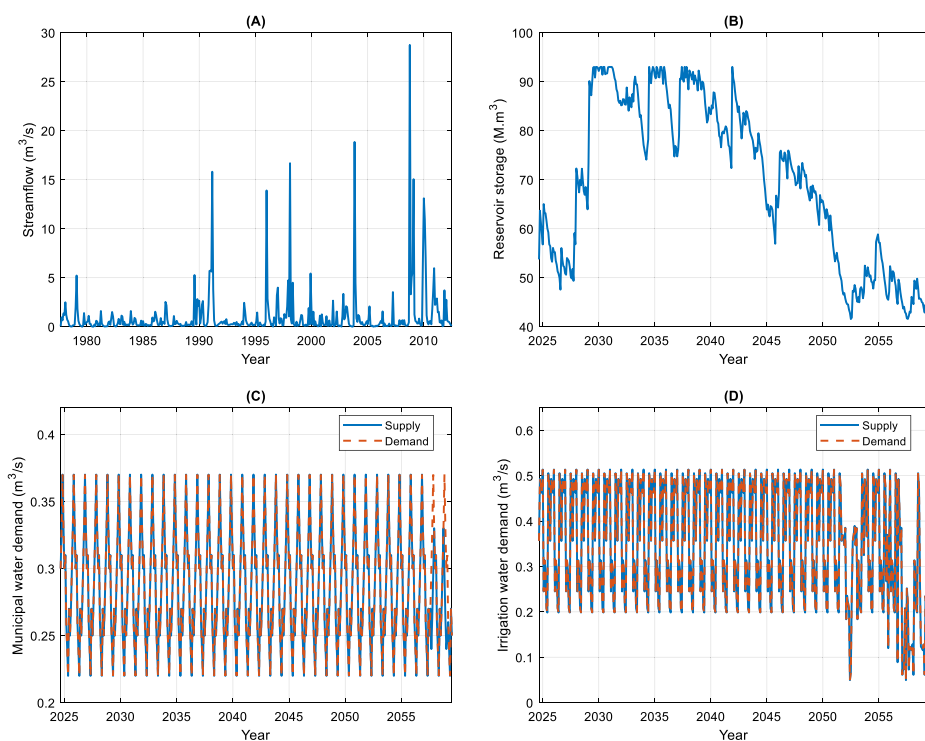


Fig. 5 Summary of the water system simulation results: (A) streamflow upstream the reservoir system, (B) water storage in the reservoir, (C) satisfaction of the MWD and (D) satisfaction of the irrigation water demand

MWD (Fig. 5C) and cover most of the irrigation demand (Fig. 5D). If dedicated exclusively to municipal supply, the reservoir could release up to $19.49 \text{ Mm}^3/\text{yr}$, exceeding the projected MWD. Under this allocation, the resulting surplus could be reallocated to irrigation. When irrigation is included in the allocation strategy, MWD remains fully satisfied and irrigation supply reaches $4.48 \text{ Mm}^3/\text{yr}$, representing 75% of the minimum acceptable delivery.

A seawater desalination plant with a capacity of $3.5 \text{ Mm}^3/\text{yr}$ would increase system reliability and help satisfy both municipal and irrigation demands. This raises the question: why was the seawater desalination plant designed with a larger capacity of $7.3 \text{ Mm}^3/\text{yr}$. We address this in the Discussion.

5.2 Statistical downscaling of GCMs projections

To analyze future climatic conditions, raw GCMs outputs were downscaled over the study area. The downscaling process was applied to average monthly observed precipitation and monthly temperature. Average precipitation was computed using the Thiessen polygon method, which weights each station's observations according to the area it represents. This approach aimed to spatially average precipitation across the basin and reduce the influence of localized variability.

Among the three tested methods, Quantile Mapping (Qmap) consistently yielded the most accurate precipitation, showing the closest match to observed values (Fig. 6). For temperature, the Linear Scaling bias correction method demonstrated the best agreement with observed data. Although all methods produced reasonable performance in downscaling GCM outputs, the RMSE values indicates substantial differences.

The downscaling methods generally reproduced the 25th, 50th and 75th percentiles of the observed dataset, indicating good performance in capturing central tendencies and intra-annual variability. However, extreme precipitation values remained poorly represented in several GCMs, particularly FIO-ESM and FGOALS, despite the application of statistical downscaling. This limitation is likely attributed to the highly variable and arid climate of the region, where extreme events are frequent and hydrologically significant (Zemzami 2015).

5.3 Hydrological response to climate change

A data-driven rainfall-runoff model was developed to evaluate the basin's hydrological response to projected climate conditions. The model was trained using observed precipitation, temperature and streamflow, with parameters optimized through a trial-and-error approach and performance evaluated using RMSE, the NSC, and the PI (Zemzami 2015). The model showed strong performance in capturing non-linear rainfall/runoff relationship ($RMSE=2.39$, $NSC=0.87$, $PI=0.98$), accurately reproducing seasonal and interannual variability with reasonable accuracy (Fig. 7, panels A and B) following extensive calibration (>5 million iteration). The calibrated model was then forced with downscaled precipitation and temperature derived from future climate projections (Fig. 7C).

Under SSP4.5, all GCMs project a reduction in inflow, ranging from -6.4% (INM-CM4-8) to -36.1% (HadGEM3), relative to the baseline. For most models, mean annual flows decrease to $20.2\text{--}29.6\text{ Mm}^3/\text{yr}$, while standard deviations (SD) varying between 12.9 and 23.6, indicating reduced water availability and higher interannual variability.

In contrast, SSP8.5 projections exhibit pronounced divergence across GCMs. Several models (e.g., GISS-E2-1-G, HadGEM3 and CanESM5) project marked reductions in inflow up to -46.1% , whereas others (e.g., FIO-ESM-2-0, FGOALS-f3-L and MIROC-ES2L) project increases ranging from $+4.9\%$ to $+26.1\%$.

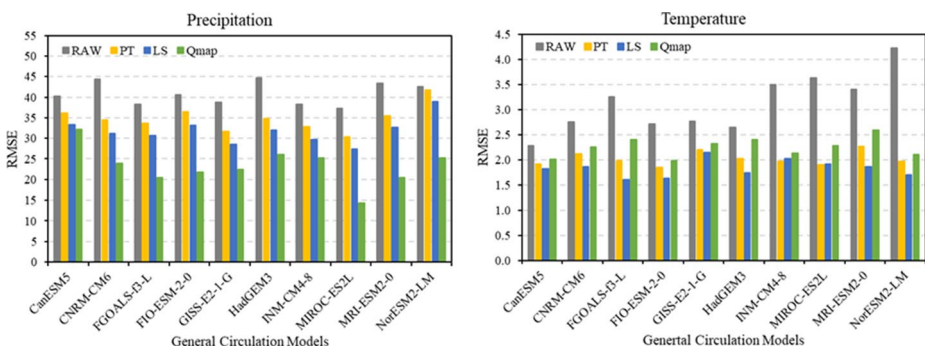


Fig. 6 Comparison of RMSE of the three downscaling statistical techniques

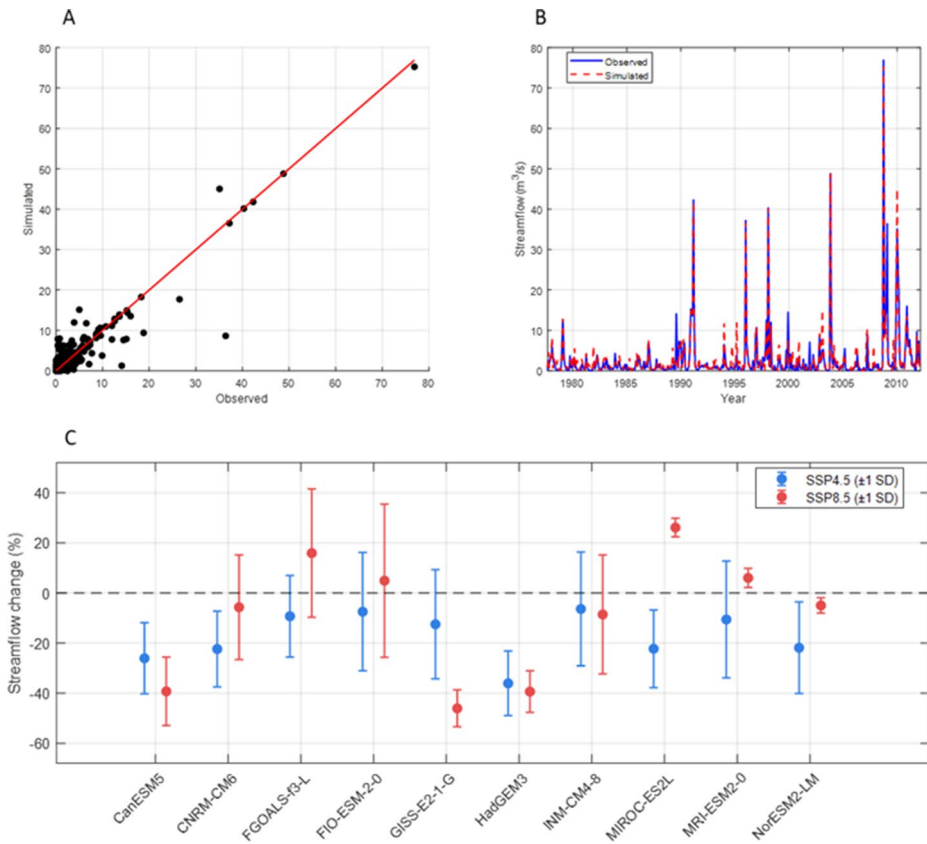


Fig. 7 Results of the hydrological simulation of Rhiss river streamflow: A) correlation between observed and simulated streamflow; B) simulated and observed streamflow time series, C) projected relative changes in mean streamflow with respect to the 1977–2012 baseline (*dots represent the ensemble mean change for each model GCM, while vertical bars indicate ± 1 standard deviation*)

5.4 Water supply under non-stationary climate futures

As shown in earlier analyses, most climate models project a reduction in annual water availability (Fig. 7C), implying decreased inflows to the Rhiss reservoir. To assess system performance under varying hydroclimatic conditions, four combined water-allocation and climate scenarios were evaluated. These scenarios were designed to assess the system's capacity to meet the required water demands associated with the different uses in the region:

- Scenario 1-1: Reservoir supplies full MWD ($15 \text{ Mm}^3/\text{yr}$) and irrigation demand ($8 \text{ Mm}^3/\text{yr}$) under SSP4.5.
- Scenario 1-2: Same allocation under SSP8.5,
- Scenario 2-1: Reservoir supplies $7.7 \text{ Mm}^3/\text{yr}$ of MWD and $8 \text{ Mm}^3/\text{yr}$ for irrigation under SSP4.5,
- Scenario 2-2: Same allocation under SSP8.5 scenario.

Scenarios 2–1 and 2–2 incorporate the contribution of the seawater desalination plant, which supplies $7.3 \text{ Mm}^3/\text{yr}$ to the municipal system. Accordingly, the reservoir supplies the remaining MWD ($7.7 \text{ Mm}^3/\text{yr}$) and provides irrigation releases as available. In the Moroccan context, irrigation demand is deemed satisfied when at least 80% of the nominal requirement is delivered.

The reservoir simulations indicate that the storage trajectories exhibited substantial variability across the different hydroclimatic scenarios (Fig. 8). The stationary baseline (black line) captures only a narrow slice of the plausible future storage states. In contrast, system vulnerability differs markedly among scenarios.

Figure 9 presents the simulated reservoir releases across the combined water-allocation and climate-forcing scenarios. The results reveal marked differences in system performance among scenarios:

- Scenario 1-1: the reservoir failed to meet MWD, with shortages ranging from 23% (MRI-ESM2-0) to 47% (NorESM2-LM), while irrigation demand was unmet across all models.
- Scenario 1-2: only two models (FGOALS-f3-L and MIROC-ES2L) satisfied the full municipal demand, and only FGOALS-f3-L model delivered a limited irrigation release ($0.75 \text{ Mm}^3/\text{yr}$). All remaining models produced municipal shortages between 18% (MRI-ESM2-0 and NorESM2-LM) and 64% (CanESM5).
- Scenario 2-1: the reservoir consistently met the reduced MWD requirement; however, irrigation supply remained insufficient, with shortages ranging from 49% (MRI-ESM2-0) to 86% (NorESM2-LM).

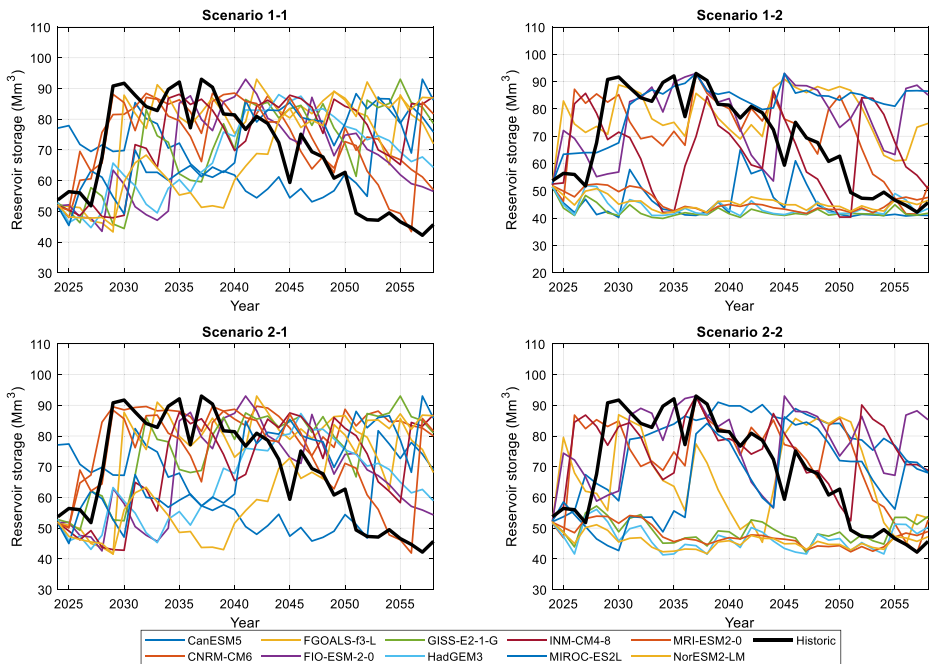


Fig. 8 Monthly water level in the reservoir according to different GCMs for the SSP 4.5 and SSP 8.5 scenarios (for clarity, only end-of-hydrological-year storage is displayed)

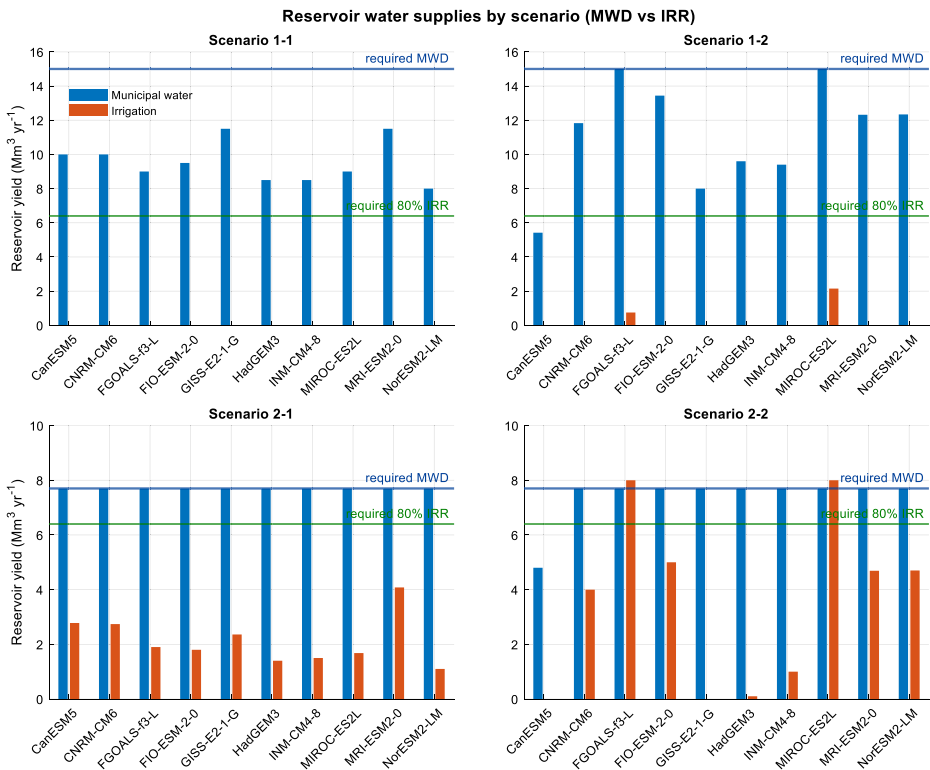


Fig. 9 Reservoir supplies for municipal and irrigation demands under climate and water allocation scenarios

- Scenario 2-2: all models except CanESM5, which recorded a 38% MWS deficit, achieved the full MWD target and released additional water for irrigation. Nevertheless, irrigation shortage remained severe, ranging from 88% (INM-CM4-8) to complete failure (CanESM5, GISS-E2-1-G and HadGEM3). Only FGOALS-f3-L and MIROC-ES2L were capable of meeting both municipal and irrigation demands.

6 Discussion

6.1 Uncertainty in hydroclimatic projections

Climate projections derived from GCMs remain indispensable for assessing the impacts of climate change on regional water resources. Yet, substantial divergences often emerge among models applied to the same basin. Such inter-model disagreements, widely reported in the literature (Yang et al. 2014; Taner et al. 2017; Brown et al. 2020; Marcos-Garcia et al. 2020; Schlef et al. 2023), highlight the uncertainties associated with future precipitation and streamflow projections. These discrepancies stem from multiple sources including:

- Model structure and parametrization (Liu Y et al. 2023).

- Initial conditions and internal variability (Raju Pathak et al. 2023).
- Resolution and spatial representation (Pan et al. 2021).
- Natural variability and feedback mechanisms.

For the Rhiss-Nekkor basin, these uncertainties translate into markedly divergent hydrological futures. Precipitation projections vary widely across models, from -33% to $+42\%$. Temperature changes are comparatively narrowed but still significant, with projected increases between $+0.76\text{ }^{\circ}\text{C}$ and $+2.27\text{ }^{\circ}\text{C}$. Consequently, projected streamflow exhibits an even broader spread, ranging from -46% to $+26\%$ relative to historical conditions.

6.2 Traditional water planning under uncertainty

Water planning in the region has long been under pressure, leading authorities to adopt a dual strategy combining seawater desalination and the Rhiss reservoir (PNE 2020). Under this approach, decision-makers allocate water according to observed and expected availability. During wet and average hydrological conditions, MWD is met through conjunctive use of reservoir storage and groundwater. In dry years, when surface water declines, desalination serves as a critical backup to ensure municipal supply.

Irrigation development was justified by the EIE Rhiss study (2017), which suggested that the Rhiss reservoir could meet the entire MWD and still release an annual surplus of approximately $8\text{ Mm}^3/\text{yr}$. Based on this study, the agriculture department proposed a new irrigation scheme drawing up to $8\text{ Mm}^3/\text{yr}$ from the reservoir. Thus, the two projects were originally designed to operate in tandem: desalination stabilizing municipal supply, and the reservoir supporting both municipal and agricultural expansion.

However, unprecedented multi-year droughts, and repeated revisions of water planning documents shifted decision-making toward crisis response rather than strategic management. Consequently, only the desalination plant has been commissioned, delivering $7.3\text{ Mm}^3/\text{yr}$ for municipal use, while the reservoir remains non-operational.

This experience illustrates how reliance on stationary design assumptions has provided a misleading sense of predictability, encouraging infrastructure decisions that overlook deep climatic uncertainty. Dependence on a single “most likely” climate trajectory increases the risk of both under- and over-investment. In contrast, robust planning approaches require embracing the different spectrums of possible futures in short-, medium- and long-term planning (Fletcher et al. 2019).

6.3 Available options under uncertainty

Reliance on a stationary planning paradigm, combined with repeated revisions of water planning documents (e.g., National Water Strategy-ongoing and 2009 edition, the National Water Plan, 2020; and the National Program for Drinking and Irrigation Supply, 2020), has resulted in systematic planning biases that have steered water management toward short-term, reactive interventions rather than coherent medium and long-term strategies.

This persistent mismatch between planning and implementation has undermined the reliability and flexibility originally envisioned. In the short term, seawater desalination remains a critical option under current hydroclimatic conditions, as it is not directly dependent on climate and can be expanded incrementally, offering a more secure water supply (SNE 2009).

Three options can be considered in this context: Option A, a conservative approach where seawater desalination is scaled to secure all water demands (23 Mm³/yr), and Option B, a more adaptive hybrid strategy where supply is shared between the reservoir and the desalination plant.

- Option A (all demands are supplied by desalination: 15 Mm³/yr for MWD and 8 Mm³/yr for irrigation): this pathway would secure both municipal and irrigation demands across all tested scenario. Yet the energy burden is high, modern seawater reverse osmosis requires approximately 3 kWh/m³ on average (Feo-García et al. 2024), equivalent to roughly 69 GWh/yr for 23 Mm³ (0.5–0.8 USD/m³). These costs may be competitive for drinking water in hydroclimatic contexts similar to the Rhiss-Nekkor region, but remain prohibitive for irrigation, requiring either tariff support or a shift to high-value crops. Affordability for local farmers is the main constraint. However, irrigation water costs could be reduced through renewable energy purchase agreements, consistent with Morocco's 2030 energy strategy to achieve 52% renewable capacity (MASEN 2025).
- Option B-1, hybrid (desalination: 15 Mm³/yr for MWD, reservoir: 8 Mm³/yr for irrigation): in this configuration, desalination secures the full MWD, while the reservoir provides 8 Mm³/yr for irrigation. This reduces the exposure of cities to drought while supporting agriculture by surface water. The energy demand is correspondingly lower than Option A, about 45 GWh/yr (15 × 3 kWh/m³), and irrigation water costs remain anchored to the reservoir. This design preserves affordability for farmers and partially relieves the reservoir from MWD pressure. However, if the desalination plant is out of service, the reservoir must still prioritize MWD, with irrigation curtailed accordingly.
- Option B-2, hybrid (desalination: 7.3 Mm³/yr for MWD, reservoir: 7.7 Mm³/yr for MWD and 8 Mm³/yr for irrigation): in this situation, desalination plant secures a baseline 7.3 Mm³/yr of MWD, while the reservoir provides the remaining 7.7 Mm³/yr for MWD and 8 Mm³/yr for irrigation. The energy demand is correspondingly lower than Option A and Option B-1, about 22 GWh/yr (7.3 × 3 kWh/m³), and irrigation water costs remain anchored to the reservoir. This arrangement maintains affordability for farmers and eases some of the pressure on the reservoir to meet MWD. However, if the system fails to fully meet MWD, municipal supply remains the top priority.

In practice, feasibility options must remain aligned with existing water infrastructure, as major projects have already been executed or are currently under construction. This reality constrains the scope of prospective alternatives, since proposals can only build upon the infrastructure currently in place. These investments constitute sunk costs (PNE 2020), that cannot be reversed; thereby limiting the scope for alternative planning pathways. Therefore, Option B-1 and Option B-2, emerge as the only realistic strategy for water managers to meet future water demands.

However, unlike the stationary approach, the yield of the Rhiss reservoir depends on future hydroclimatic conditions. Reduced inflows in drier scenarios would curtail its contribution, forcing desalination to run at higher capacity, with significant implications for energy consumption, financial costs and irrigation supply. The ambitious irrigation project, originally justified under stationary assumptions of surplus water, is the most vulnerable component of the system. Consequently, the project risks undermining private sector investments already committed to its development.

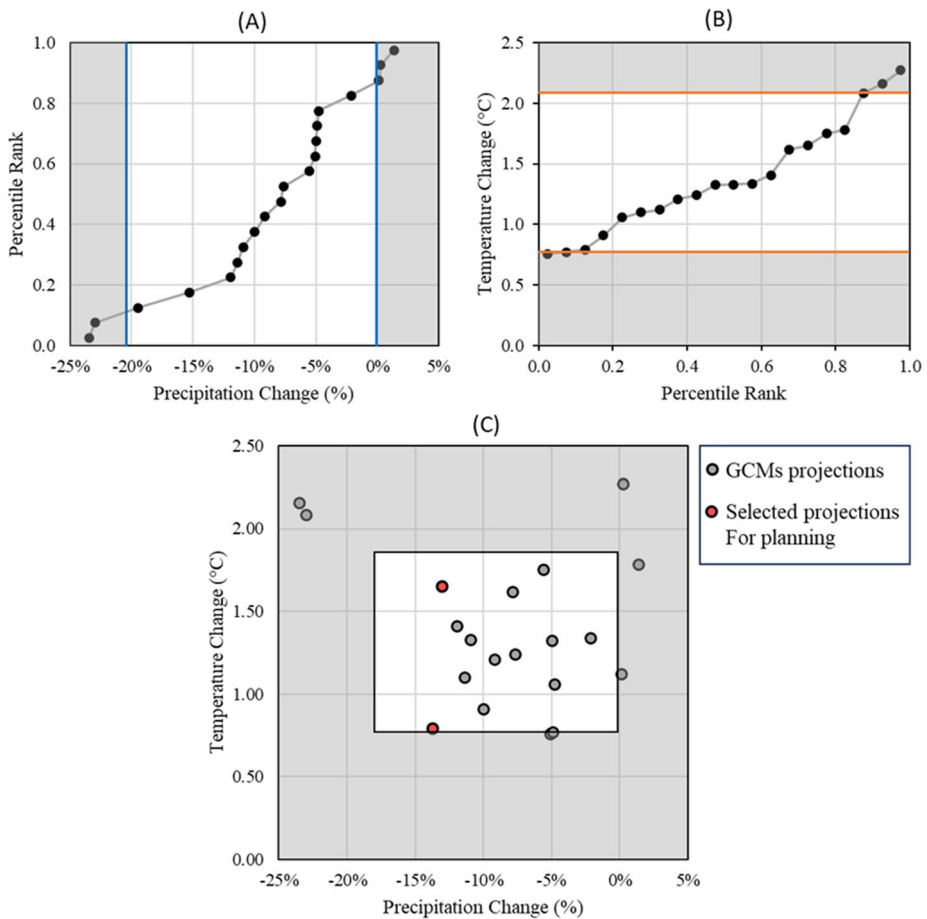


Fig. 10 Projected climate possibilities illustrated by change range of precipitation and temperature

6.4 Rethinking water planning

Because of the current water management strategy, any revision of planning must operate within the framework of existing projects, aiming to optimize their performance rather than proposing entirely new trajectories. Despite the advantages of climate modeling, the wide spread among GCM projections produces multiple plausible futures, making decision-making inherently challenging. For instance, which climatic trajectory should planners adopt when determining the appropriate desalination capacity?

To address decision-making challenges under climate change in the Rhiss-Nekkor basin, we examined the key climatic variables (Fig. 10) that illustrate the complexity of water project planning under climatic uncertainty. Panels 10-A and 10-B illustrate the distributions of projected annual precipitation and temperature, respectively, with blue and orange lines indicating the 10th and 90th percentiles change ranges. Panel 10-C presents paired precipitation-temperature changes, highlighting the range of potential future climate conditions. The spread of projected precipitation and temperature values define the spectrum of

plausible climate futures for the region by 2050, extending from relatively cooler and drier conditions to significantly warmer and wetter scenarios.

The plausible climate trajectories confirm the region's warming and drying trends, consistent with findings from other studies (Zittis et al. 2021, 2022). The main challenge at this stage is translating climate model outputs into information that decision-makers can perceive as actionable. The diversity of GCM-based projections made it difficult to provide the level of certainty typically sought in water resources planning. This difficulty was compounded by decades of designing and planning water projects using observed hydroclimatic data under the assumption of stationarity. Discussions with water managers revealed that stakeholders often interpreted climate projections as deterministic forecasts, thereby limiting their perceived usefulness for planning under uncertainty.

Rather than advocating for a single most likely scenario, we worked collaboratively with decision-makers to define a limited set of planning-relevant projections. These scenarios were chosen for their practical relevance rather than statistical likelihood. Stakeholder discussions identified declining annual precipitation as the dominant concern, outweighing temperature increases and flood risks. This perception guided scenario design to ward drier climate conditions, ensuring that the analysis directly addresses the most critical and immediate planning challenges.

Figure 10C summarizes the two selected climate projections, illustrating the alignment between modeled futures and stakeholder-defined priorities. They form the basis for testing the robustness of planned water infrastructure under conditions of prolonged aridity, a shift that marks an important departure from traditional reliance on observed hydroclimatic data.

These two projections represent conditions under which the Rhiss-Nekkor water supply is likely vulnerable. Under both scenarios, the reservoir yields only 4.8 Mm³/yr and 5.4 Mm³/yr, insufficient to meet irrigation needs, requiring desalination expansion to fully cover municipal demand. The only option capable of reducing MWS shortages while sustaining the irrigation project is to expand desalination capacity to 16.6 Mm³/yr (covering 80% of irrigation demand) or 18.2 Mm³/yr (covering 100%).

In both scenarios, the desalination plant plays a central role in securing MWS, which remains the highest management priority. However, meeting irrigation demand is considerably more challenging, especially under the anticipated shift toward drier and warmer climatic conditions.

7 Conclusions

The Moroccan approach to water resources planning has been challenged by climate non-stationarity, both in its design and implementation, leading to outcomes that are largely misaligned with the intended objectives. By integrating climate projections, this article demonstrates that future hydroclimatic conditions are characterized by declining inflows, increased variability, and substantial uncertainty across climate models. These changes significantly challenge the ability of existing water infrastructure, originally designed under stationary assumptions, to reliably meet future water demands.

Scenario analyses reveal that reservoir-based supply alone is insufficient to secure municipal and irrigation water demands under most projected futures. Although the integration of seawater desalination markedly improves municipal water supply reliability, it does not

fully offset the impacts of reduced and more variable inflows, and irrigation deficits remain widespread across scenarios. These findings emphasize that reliance on single deterministic projections or historical hydrological conditions can mask system vulnerabilities and lead to overconfident planning outcomes.

More broadly, the results underscore the need to transition from stationary, supply-oriented planning paradigms toward adaptive and uncertainty-aware decision frameworks. Incorporating ensembles of climate projections, explicitly testing alternative allocation strategies, and combining conventional infrastructure with non-conventional water sources are essential steps toward enhancing system robustness under deep hydroclimatic uncertainty. While grounded in the Morocco context, the methodological framework and insights are transferable to other water-stressed regions facing similar climatic and institutional challenges. Future work should focus on integrating economic, environmental, and governance dimensions to further support climate-resilient water resources planning.

Acknowledgements The author gratefully acknowledges Professor Patrick J. Ray (University of Cincinnati), Professor Casey Brown (University of Massachusetts) and Ing. Pravin Karki, Senior Hydropower Specialist at the World Bank Group, for their guidance on water resources planning under uncertainty. Their insights into system design under deep uncertainty and climate change significantly informed the conceptual framework and methodological approach of this study. The authors thank the anonymous reviewers for their very helpful critiques on earlier versions of this paper.

Author contributions Zemzami Mahmoud: Conceptualization, Methodology, Programming, testing and implementation, Modeling, Formal analysis, Writing - original version, revisions and modifications. Hajar Habib: Modeling, Formal Analysis, Writing, Validation. Souad Haida: Conceptualization, Methodology, Validation, Writing - revisions and modifications, Supervision.

Funding Not applicable.

Data availability Hydroclimatic data are available under a specific and reasonable request.

Declarations The authors declare that this research received no external funding. On behalf of all authors, the corresponding author states that there is no conflict of interest.

Consent for publication All authors agreed on the content of the paper.

Competing interests The authors declare that they have no conflicts of interest.

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