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Analysis of Dez Dam's Operational Performance in Meeting Downstream Water Demands Under Future Climate Scenarios

Elaheh Asgari [1*], **Hossein Ghorbani** [2]

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ABSTRACT

Climate change and its associated impacts pose a significant challenge for water-resource management, especially in basins where reservoir operations are critical for meeting domestic, agricultural, industrial, and environmental water demands. This study evaluated how climate change will affect the operational performance of Dez Dam, located in southwestern Iran, and its ability to meet downstream water demands in the future. To this end, daily climate projections (precipitation and minimum/maximum temperatures) from five General Circulation Models (GCMs) under two emission scenarios (RCP4.5 and RCP8.5) were downscaled using quantile mapping and combined with Bayesian Model Averaging (BMA). We then simulated inflow to the Dez Dam reservoir using the semi-distributed Soil and Water Assessment Tool (SWAT) model. Finally, these results were fed into the MODSIM water-allocation model to assess the reservoir's performance in meeting various downstream demands across a baseline period (1984–2018) and three future periods: 2041–2060, 2061–2080, and 2081–2100. The results indicated that the Dez Basin's future climate will be characterized by decreased precipitation and increased temperatures. By the end of the century, total annual precipitation is projected to drop by approximately 17–18% under both RCP4.5 and RCP8.5 scenarios, while maximum and minimum temperatures are expected to show substantial increases. Reduced precipitation during winter and early spring—the basin's primary runoff-generation period—will lead to a significant decline in reservoir inflow. SWAT model results reveal that during the far-future period (2081–2100), the mean annual streamflow of the Dez River will decline by 56.8% under RCP4.5, while a more substantial reduction of 64.2% is projected under RCP8.5 compared to the baseline period of 1984–2018. The MODSIM assessment of reservoir performance showed that declining basin inflows will limit Dez Dam's operational capacity. While higher-priority demands, such as domestic water supply and Ghadeer industrial demand, are expected to maintain relatively high supply reliability, agricultural, environmental, and other downstream demands will face substantial reductions in future water supply. Specifically, the supply percentage for agricultural demands in Dez and Band-e Qir is projected to fall below 30% by the end of the century. Overall, these findings suggest that climate change may reduce the reliability of Dez Dam's operations, highlighting the need to revise water-allocation policies, manage demand, improve water-use efficiency, and develop adaptation strategies for future climatic conditions.

Keywords:

MODSIM, SWAT, Hydrological Modeling, Climate Change, Dez Dam

[1] *Postdoctoral Researcher in Climatology, Faculty of Geography and Environmental Sciences, Hakim Sabzevari University, Sabzevar, Iran.*
[2] *PhD of Climatology, Faculty of Geography and Environmental Sciences, Hakim Sabzevari University, Sabzevar, Iran.*

[*]*Corresponding Author: Email: elaheh.asgari2011@gmail.com/ ORCID: 0000-0003-1927-2658*

1. Introduction

In recent decades, climate change has emerged as one of the most significant challenges in global water resource management. Rising global temperatures, shifts in the spatiotemporal patterns of precipitation, and the intensification of extreme events like droughts and floods have impacted the primary processes of the hydrological cycle, including evapotranspiration, soil moisture, and river flow regimes (Wang et al., 2024). These changes increase uncertainty in estimating future water resources and highlight the necessity of revising current water resources planning and management strategies.

This challenge is particularly significant in arid and semi-arid regions, which inherently have limited water resources and more pronounced hydrological variability. By reducing runoff, increasing evaporation, and altering the timing of river flows, climate change disrupts the balance between water supply and demand and affects the efficiency of water supply systems (Lin et al., 2024). Therefore, relying solely on historical data is no longer sufficient for water resources planning under future conditions. The use of climate scenarios to evaluate the performance of water resource systems has become essential for sustainable management.

Iran, situated in the world's arid and semi-arid belt, is highly vulnerable to climate change. Increasing temperatures, diminishing renewable water resources, recurrent hydrological droughts, and rising water demand have strained both surface and groundwater supplies (Nasirian & Naddafi, 2025). Consequently, evaluating the performance of water infrastructure, especially dam reservoirs which are vital for regulating flow and supplying water for domestic, agricultural, and industrial use, and hydropower generation, is crucial. Climate change can impair the operational effectiveness of these systems by decreasing inflows, increasing evaporation from reservoir surfaces, and altering the seasonal timing of runoff. Therefore, assessing reservoir performance must go beyond hydrological changes to include their capacity to meet downstream water demands reliably and sustainably (Muhammad et al., 2020; Nguyen et al., 2022; Qin et al., 2022; Schmitt & Rosa, 2024).

Assessing the performance of water resource systems necessitates integrating hydrological and water-allocation models. Hydrological models, such as SWAT, simulate runoff under various climate scenarios. This simulated runoff then serves as input for water-allocation models, like MODSIM, which account for reservoir capacities, operating rules, system constraints, and water-use priorities. This integrated approach allows for evaluating reservoir operational performance and determining the degree to which various water demands can be met under future climate conditions. Furthermore, employing an ensemble of regional climate models, rather than relying on a single model, makes it possible to better represent uncertainties in climate projections and to provide more realistic estimates of future conditions (Fereidoon& Koch, 2018).

Previous studies in the Dez River Basin have primarily focused on estimating hydrological changes, simulating inflows, or assessing hydropower generation. However, a review of the literature reveals two major challenges and research gaps. First, a direct link between climate-induced changes in the hydrological regime and reservoir operation dynamics—specifically, how these changes affect the ability to meet multipurpose downstream water demands (domestic, agricultural, and environmental)—has rarely been analyzed within an optimal water allocation modeling framework. Second, most studies have evaluated system performance using individual climate models or without fully accounting for the complete chain of uncertainty, which limits the robustness of the results for management decision-making (Mousavi., 2017; Asgari et al., 2024).

Therefore, the present study aims to analyze the operational performance of the Dez Dam in meeting downstream water demands under various climate change scenarios. The main novelty of this study lies in developing an integrated modeling framework (climate–hydrology–allocation chain). This framework moves beyond purely hydrological assessments by establishing a direct and systematic link between runoff changes and reservoir operating rules, thereby tracing the impacts of climate change through to the downstream end-use demands. Additionally, by employing an ensemble of five GCMs, this study incorporates climate uncertainties into the operational analysis in a structured manner and translates them into operational risk indicators such as reliability, resilience, and vulnerability. Finally, a distinguishing

feature of this study, compared to conventional one-dimensional approaches to water resources management, is its emphasis on a balanced, multi-criteria assessment of downstream sectoral demands. This includes the simultaneous analysis of the sensitivity and vulnerability of agricultural water use, environmental water requirements, and reservoir storage sustainability under future climate stresses

2. Data and Methodology

Study Area

The Dez River Basin is geographically located between 48°10′ and 50°21′ E longitude and 31°34′ and 34°07′ N latitude. The total area of the basin is approximately 21,720 km², with a mean elevation of about 1,600 m above sea level. The study area comprises the portion of the Basin upstream of Dez Dam, covering an area of 17,365 km².

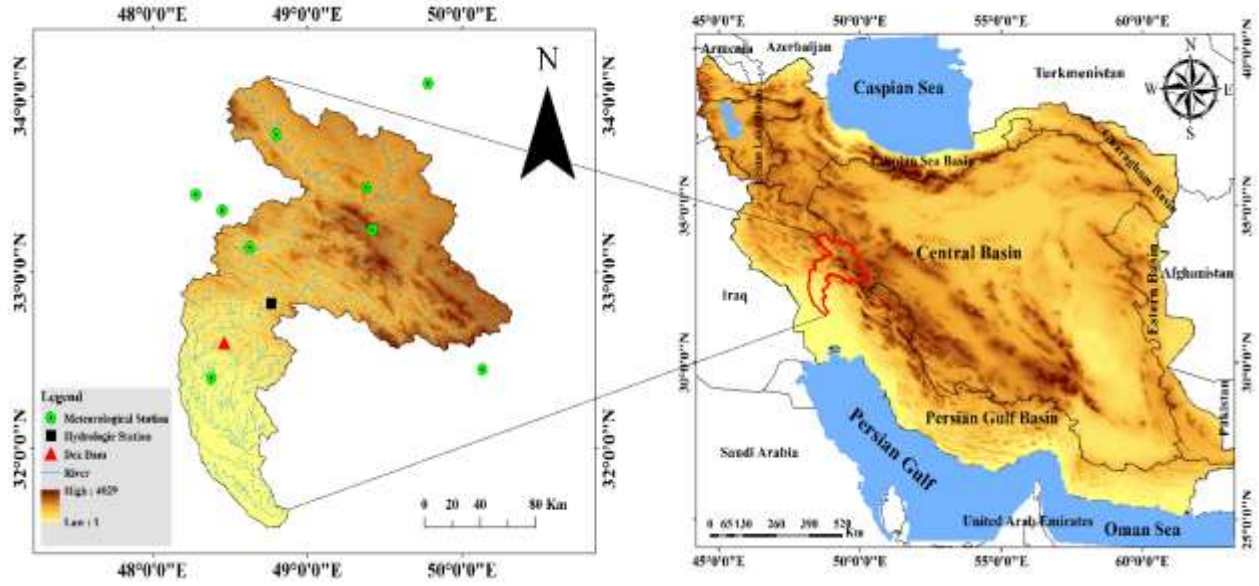


Figure 1. Location of the Dez River Basin within the Great Karun Basin

General Research Framework

This study developed an integrated climate–hydrological–water allocation framework to assess the impacts of climate change on the operational performance of Dez Dam. The framework comprises three main stages. In the first stage, the climate datasets from the Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs were obtained for future periods. These outputs were then bias-corrected using the Quantile Mapping (QM) method, and subsequently integrated through Bayesian Model Averaging (BMA) to generate a set of future climate data with reduced uncertainty.

In the second stage, the generated climate data was used as inputs to the Soil and Water Assessment Tool (SWAT) hydrological model. This simulated changes in inflow to the Dez Dam reservoir under future climate scenarios. In the third stage, the simulated inflows were transferred to the MODSIM water-allocation model to evaluate reservoir operational performance and the system's capability to meet downstream water demands. Finally, changes in dam performance during future periods, relative to the baseline period, were analyzed using water-supply indicators.

Climate Data and Future Climate Projections

Daily meteorological data, including precipitation and minimum and maximum temperatures, were obtained from the Iran Meteorological Organization (www.irimo.ir) for the baseline period (1984–2018) to run the hydrological model. Additionally, daily streamflow data, recorded at the Taleh Zang gauging

station, were acquired from the Iran Water Resources Management Company (www.wrm.ir). To assess the impacts of future climate change, outputs from five GCMs of the Coupled Model Intercomparison Project Phase 5 (CMIP5) were extracted from the Copernicus Climate Data Store database (Table 1). The selection of these specific GCMs was grounded in empirical evidence and regional performance evaluations in southwestern Iran; previous studies in the Dez and Karun river basins (e.g., Eini et al., 2021; Saadi et al., 2020) demonstrated their superior capability and robustness in reproducing historical hydro-climatological patterns across the Zagros region, thereby minimizing model-related structural uncertainties.

Table 1. Characteristics of the climate models used in this study

Model No	Climate Model	Developing Research Institution(s)
M1	EC-EARTH	European community, Europe
M2	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M), Germany
M3	MIROC5	Atmosphere and Ocean Research Institute (AORI), NIES, and JAMSTEC, Japan
M4	NorESM1-M	NCC, Norwegian Climate Center
M5	CNRM-CM5	Centre National de Recherches Météorologiques / CERFACS, France

Quantile Mapping Method

The Quantile Mapping (QM) method, a statistical bias-correction approach widely used in climate-impact and hydrological studies (Teutschbein and Seibert, 2012; Cannon et al., 2015), was employed to correct systematic biases in the daily precipitation and temperature series. Unlike conventional scaling methods that adjust only selected statistical moments, QM establishes a transfer relationship between the cumulative distribution functions (CDFs) of simulated and observed data and therefore corrects the distribution across a broad range of quantiles.

In this study, an empirical quantile mapping (eQM) approach was applied to the daily time series separately for each calendar month. Thus, a specific transfer function was established for each month to account for the pronounced seasonal characteristics of precipitation and temperature in the Dez basin. For a simulated daily value $X_{GCM,h}(t,m)$during the historical baseline period, the bias-corrected value $X_{BC,h}(t,m)$was obtained as:

$$X_{BC,h}(t,m) = F_{obs,m}^{-1}\left[F_{GCM,h,m}\left(X_{GCM,h}(t,m)\right)\right] \quad (1)$$

where $X_{GCM,h}(t,m)$denotes the raw daily GCM value on day $t$of calendar month m, $F_{GCM,h,m}$represents the empirical CDF of the historical GCM simulation for month m, and $F_{obs,m}^{-1}$denotes the empirical quantile function of the corresponding observed station data for the same month.

For precipitation, a wet-day threshold of 0.1 mm day^{-1}was applied before CDF matching to reduce the influence of spurious light precipitation (the drizzle effect) in the climate-model simulations. Simulated precipitation values below this threshold were set to zero. The same thresholding procedure was consistently applied to the historical and future precipitation series.

For future projections, the transfer functions derived from the baseline period were applied to the corresponding future GCM simulations as follows:

$$X_{BC,f}(t,m) = F_{obs,m}^{-1}\left[F_{GCM,h,m}\left(X_{GCM,f}(t,m)\right)\right] \quad (2)$$

where $X_{GCM,f}(t,m)$represents the raw future GCM value and $X_{BC,f}(t,m)$is the corresponding bias-corrected value. The transfer functions were calibrated exclusively over the baseline period and subsequently applied to the future projections to maintain consistency between historical calibration and future correction.

For simulated future values falling outside the historical calibration range, linear extrapolation of the empirical transfer function was applied following the approach described by Cannon et al. (2015), thereby avoiding artificial truncation of projected values at the historical upper or lower bounds.

Bayesian Model Averaging

Bayesian Model Averaging (BMA) was implemented following the hydrological ensemble framework developed by Duan et al. (2007) to aggregate projections from the five bias-corrected GCMs and explicitly quantify modeling uncertainty. BMA generates a predictive probability density function (PDF) that represents a weighted combination of individual model predictive densities, with weights reflecting each model's relative predictive skill during the calibration period.

Let $y_t$be the observed hydro-climatic variable at time step $t$and $f_{k,t}$be the forecast from the k-th climate model ($k = 1, \dots, K$; here $K = 5$). The BMA predictive PDF of $y_t$conditional on the multi-model ensemble forecast $\mathbf{f}_t = (f_{1,t}, \dots, f_{K,t})$is given by:

$$p(y_t \mid \mathbf{f}_t) = \sum_{k=1}^{K} w_k \; g_k\left(y_t \mid f_{k,t}, \sigma_k^2\right) \tag{3}$$

where $w_k$is the posterior probability (weight) of model M_k, constrained to be non-negative ($\sum_{k=1}^{K} w_k = 1$, $w_k \geq 0$), and $g_k(y_t \mid f_{k,t}, \sigma_k^2)$is the conditional PDF of $y_t$given the forecast $f_{k,t}$with variance σ_k^2. Following Duan et al. (2007), $g_k$is specified as a normal distribution $\mathcal{N}(f_{k,t}, \sigma_k^2)$.

Parameter Estimation via the Expectation-Maximization (EM) Algorithm:

The unknown parameters $\theta = \{w_k, \sigma_k^2\}_{k=1}^{K}$were estimated by maximizing the log-likelihood function over the baseline training dataset (T time steps) using the Expectation-Maximization (EM) algorithm (Duan et al., 2007):

Expectation Step (E-step): The latent variable $z_{k,t}$, representing the posterior probability that model $k$generated observation y_t, is computed at iteration (j)as:

$$z_{k,t}^{(j)} = \frac{w_k^{(j)} \; g(y_t \mid f_{k,t}, \sigma_k^{2(j)})}{\sum_{l=1}^{K} w_l^{(j)} \; g(y_t \mid f_{l,t}, \sigma_l^{2(j)})} \tag{4}$$

Maximization Step (M-step): The weights and model variances are updated as:

$$w_k^{(j+1)} = \frac{1}{T} \sum_{t=1}^{T} z_{k,t}^{(j)} \tag{5}$$

$$\sigma_k^{2(j+1)} = \frac{\sum_{t=1}^{T} z_{k,t}^{(j)} \, (y_t - f_{k,t})^2}{\sum_{t=1}^{T} z_{k,t}^{(j)}} \tag{6}$$

Iterations were repeated until the change in log-likelihood fell below a convergence tolerance of 10^{-6}.

Deterministic Forecast and Prediction Intervals:
The deterministic BMA ensemble mean, representing the expected hydro-climatic forecast, is:

$$E(y_t \mid \mathbf{f}_t) = \sum_{k=1}^{K} w_k f_{k,t} \tag{7}$$

with a total ensemble predictive variance computed as:

$$\mathrm{Var}(y_t \mid \mathbf{f}_t) = \sum_{k=1}^{K} w_k (f_{k,t} - E(y_t \mid \mathbf{f}_t))^2 + \sum_{k=1}^{K} w_k \sigma_k^2 \tag{8}$$

where the first term reflects between-model variability and the second term accounts for within-model uncertainty. The 90% uncertainty prediction interval (spanning the 5th to 95th percentiles) was derived from the BMA cumulative distribution to quantify projection uncertainty for the SWAT simulations.

Hydrological Simulation using the SWAT Model
The SWAT (Soil and Water Assessment Tool) hydrological model was employed to simulate inflow into the Dez Dam reservoir. This physical, semi-distributed, and continuous-time model is capable of simulating hydrological processes at the basin scale and assessing the impact of various climate scenarios on hydrological cycle components (Arnold et al., 2012).
Input data for the model included a 90-meter spatial resolution Digital Elevation Model (DEM), a land use map, an FAO soil map, and daily meteorological data. Following basin boundary delineation, the model subdivided the basin into Hydrologic Response Units (HRUs) based on soil type, land use, and slope classes. For this research, the basin was partitioned into 104 sub-basins and 312 Hydrologic Response Units. The SWAT model calculates soil water content using the water balance equation (Equation 3). In this study, surface runoff was simulated using the Soil Conservation Service (SCS) Curve Number method, evapotranspiration with the Hargreaves method, and streamflow routing in river channels using the Muskingum method.

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \tag{9}$$

Model calibration, uncertainty analysis, and validation were performed using the SUFI-2 algorithm within the SWAT-CUP software package (Abbaspour et al., 2007; Abbaspour, 2011). The model's performance was assessed using the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and the P-factor and R-factor indices.
Daily discharge data from the Telezang gaging station, spanning 1984 to 2018, were acquired from the Iran Water Resources Management Company. The initial two years (1984–1985) served as the model's warm-up period. Calibration was conducted for 1986–2005, and validation for 2006–2018.

MODSIM Water Allocation Model and Reservoir Operation Simulation
The MODSIM water allocation model was employed to assess the operational performance of the Dez Dam. This model simulates the entire water resources network, encompassing reservoirs, river channels, and demand centers, thereby facilitating the analysis of water allocation patterns and system performance across diverse conditions (Labadie, 2010). For this study, inflow hydrographs simulated by the SWAT

model served as input data for MODSIM. The model was run with a monthly time step, and water allocation priorities were established in accordance with national water resources allocation guidelines. Figure 2 illustrates the topology of the Dez River basin within the MODSIM framework.

The technical specifications for the Dez Dam reservoir, its hydroelectric power plant, conveyance constraints, and downstream water demands—including municipal, industrial, agricultural, and minimum environmental flow requirements—were acquired from the Khuzestan Water and Power Authority (KWPA). In the MODSIM setup, the reservoir's maximum capacity was set at 3361 MCM, with an active storage of 2436 MCM, dead storage of 925 MCM, and an initial storage of 2900.24 MCM at the start of the simulation (1986). Evaporation losses were calculated based on local meteorological data and the reservoir surface area derived from hydraulic characteristic curves (Figure 3). Turbine efficiency and tailwater-outflow relationships were incorporated to model hydropower operation. Reservoir management followed a rule-curve approach, with the target volume set to the maximum capacity to optimize supply and power generation. For future scenarios, it was assumed that existing operational protocols remain static, with system performance variations driven solely by climate-projected inflow hydrographs.

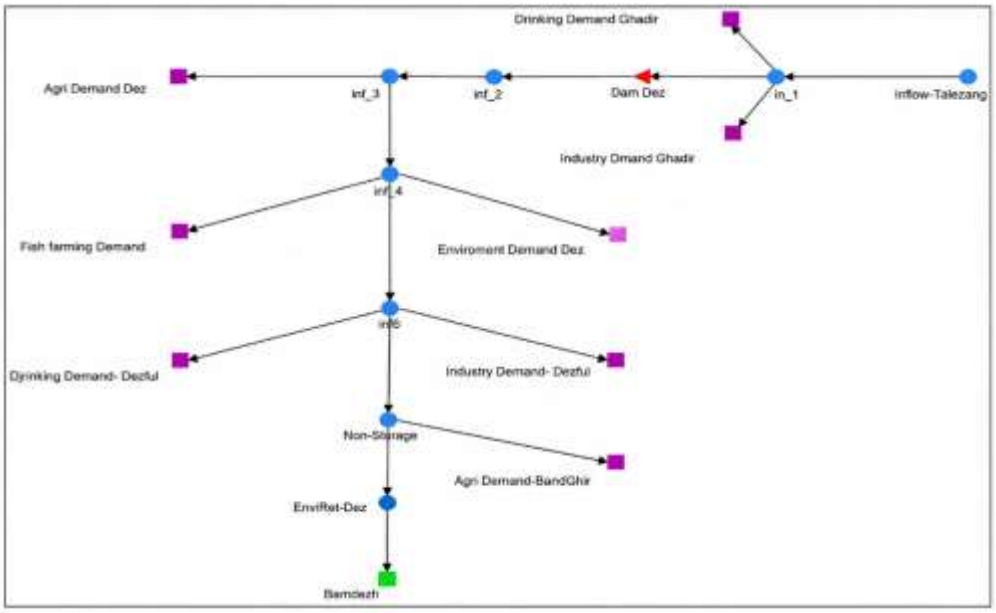


Figure 2. Topology of the Dez river basin in the MODSIM model

Reservoir Operation Performance Evaluation Indices

The operational performance of the Dez Dam system was evaluated using two standard performance metrics proposed by Loucks and van Beek (2005): temporal reliability (Rel_T) and volumetric reliability (Rel_V). These indices quantify the extent to which target water demands are satisfied in terms of duration and total volume:

1. **Temporal Reliability (Rel_T):** Represents the percentage of time steps (months) during the simulation period in which the target water demand was fully satisfied without deficit:

$$Rel_T = \left(\frac{N_s}{N}\right) \times 100 \tag{10}$$

where $N_s$is the number of months in which demand was completely met, and $N$is the total number of months in the simulation period.

2. **Volumetric Reliability (Rel_V):** Measures the ratio of the total water volume supplied to the total water volume demanded over the entire simulation horizon:

$$Rel_V = \left(\frac{\sum_{t=1}^{N} S_t}{\sum_{t=1}^{N} D_t}\right) \times 100 \tag{11}$$

where $S_t$is the volume of water supplied in month t, and $D_t$is the water demand in month t.

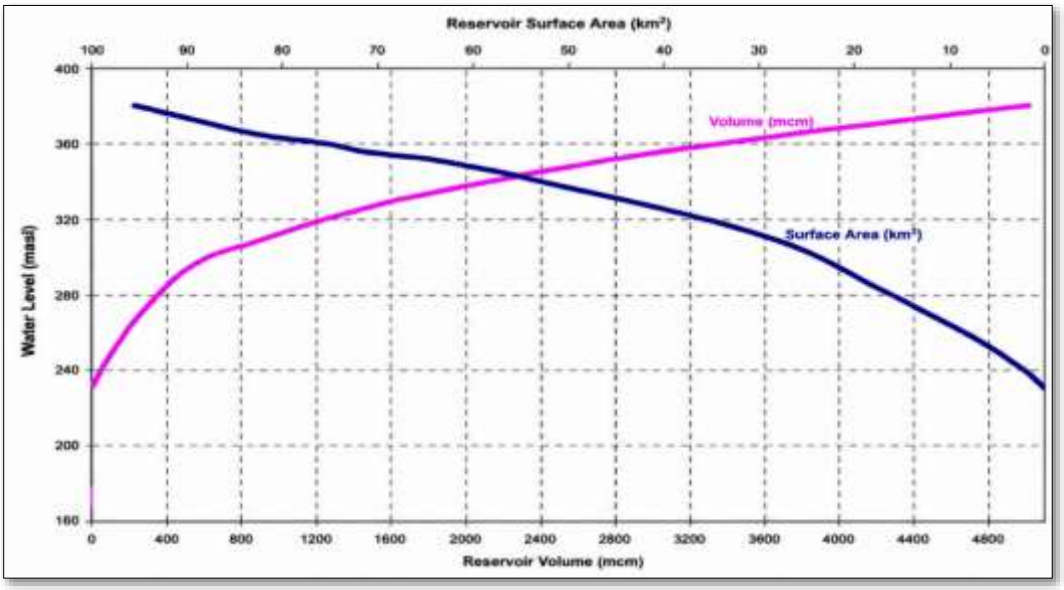


Figure 3. Dez Dam reservoir surface area and volume values at various elevations

3. Results

3.1. Changes in Precipitation under Future Climate Scenarios

Figures 4(a) and 4(b) illustrate the projected monthly and annual precipitation changes in the Dez Basin under the RCP4.5 and RCP8.5 scenarios. The results indicate a gradual decline in annual precipitation under both emission scenarios. Specifically, total annual precipitation is projected to decrease by 11.3%, 13.3%, and 17.2% under the RCP4.5 scenario, and by 8.5%, 15.2%, and 18.0% under the RCP8.5 scenario, relative to the baseline period. These findings suggest that although the differences between the two scenarios are negligible in the near future, the rate of precipitation decline accelerates during the second half of the century as greenhouse gas emissions intensify. By the end of the century, annual precipitation is projected to decrease by 17.2% under RCP4.5 and 18% under RCP8.5.

The rainy season's timing remains largely consistent, with most precipitation still occurring in winter and early spring. However, the amount of precipitation is projected to decrease across most wet months. Reductions in December, January, and February are particularly significant, as these months substantially contribute to runoff generation and the recharge of the Dez Reservoir. Minor changes in autumn precipitation are insufficient to offset the decline in winter rainfall. Furthermore, the continued very low

precipitation from June to September suggests that climate change is more likely to reduce the intensity of effective annual precipitation rather than alter the seasonal precipitation regime.

3.2. Changes in Maximum and Minimum Temperatures under Climate Change

Figures 4(c) and 4(d) illustrate the projected changes in maximum temperature within the Dez Basin under various future climate scenarios. A consistent increase in annual maximum temperature is anticipated across all future periods, with the rate of warming varying between the two emission scenarios.

Under the RCP4.5 scenario, the annual mean maximum temperature is projected to rise by 1.49°C, 2.49°C, and 3.07°C, respectively. In contrast, the RCP8.5 scenario forecasts more significant increases, reaching 1.55°C, 3.58°C, and 5.85°C for the corresponding periods. These findings highlight that the impact of emission pathways on maximum temperature becomes considerably more pronounced after mid-century. By the end of the century, warming under RCP8.5 is projected to be almost double that under RCP4.5.

The monthly temperature patterns reveal year-round warming, with the most substantial increases expected during the warm season. Specifically, under the RCP8.5 scenario for the 2081–2100 period, summer maximum temperatures are projected to exceed 42°C. This indicates that climate change will not only elevate average temperatures but also intensify the severity of summer heat.

Like maximum temperature, minimum temperature consistently shows a warming trend under both emission scenarios (Figure 4(e,f)). The annual mean minimum temperature is projected to rise by 1.52°C, 3.26°C, and 4.23°C under the RCP4.5 scenario, and by 2.71°C, 3.82°C, and 5.28°C under the RCP8.5 scenario, all relative to the baseline period. This increase in minimum temperature is more pronounced than that of maximum temperature, especially in the near future. This suggests greater nighttime warming and a narrower diurnal temperature range, a trend widely documented in previous climate change research.

Monthly projections also show that the most significant increases in minimum temperature will occur during the cold season. Consequently, sub-zero winter temperatures are expected to become progressively less frequent, leading to milder winters. These shifts are anticipated to affect temperature-dependent hydrological processes, such as snowmelt dynamics in mountainous regions and the timing of runoff generation.

In summary, the results in Figure 4(a–f) indicate that the Dez Basin's future climate will be marked by reduced effective precipitation and substantial increases in both minimum and maximum temperatures. While the seasonal timing of precipitation and temperature largely remains consistent, the magnitude of climate change intensifies considerably after mid-century, particularly under the RCP8.5 scenario. The simultaneous decrease in precipitation and increase in temperature point to heightened climatic aridity and growing water deficits throughout the Basin. These changes are expected to decrease runoff generation, increase evaporative losses, and intensify water demand, thereby negatively impacting the operational performance of the Dez Reservoir.

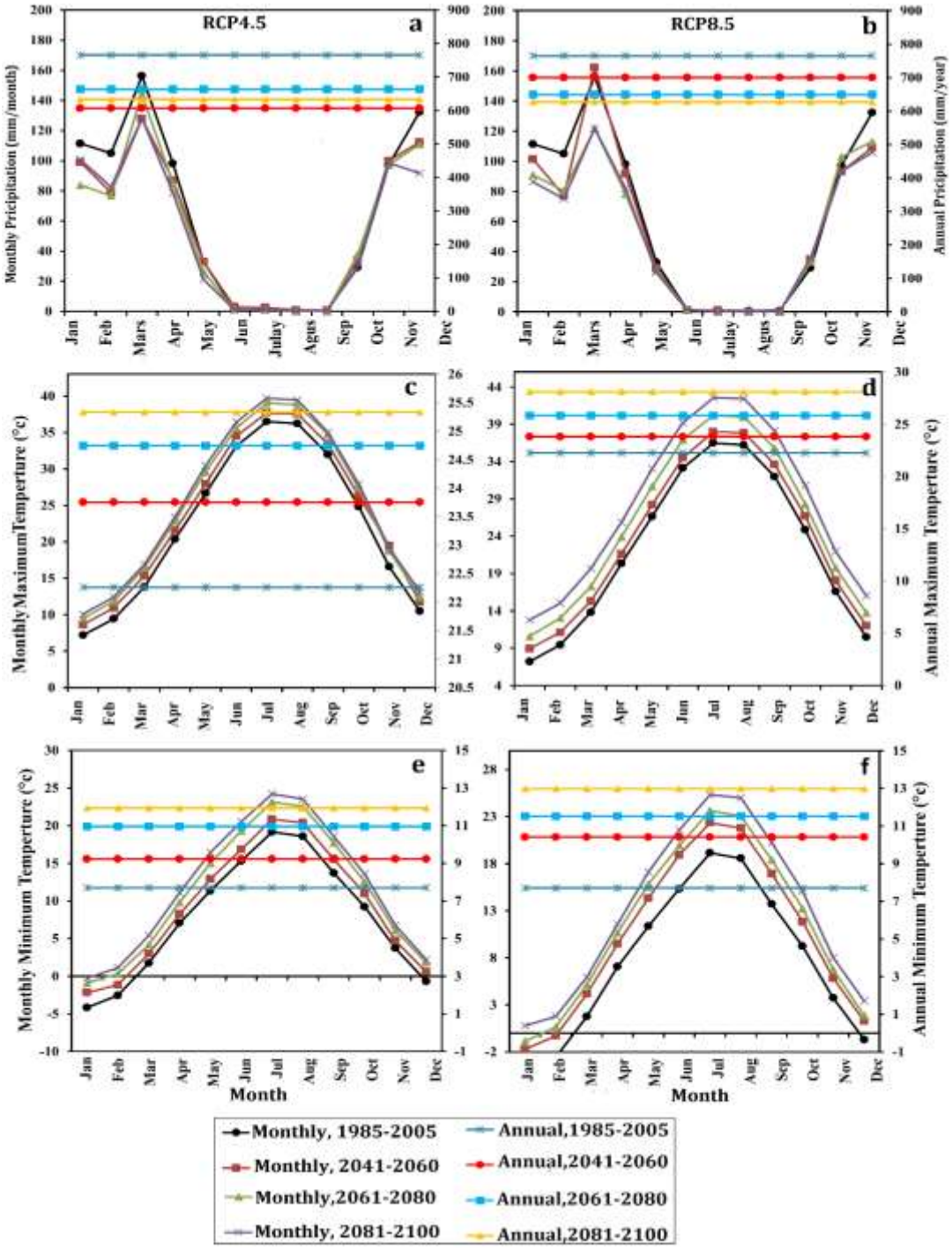


Figure 4. Monthly mean precipitation (a, b), maximum temperature (c, d), and minimum temperature (e, f) across the entire Dez Basin under the RCP4.5 and RCP8.5 scenarios, respectively, for the 2040s, 2060s, and 2090s relative to the baseline period.

3.3. Sensitivity Analysis and Calibration of the SWAT Model

In this study, a global sensitivity analysis using the SUFI-2 algorithm was performed to identify the parameters influencing streamflow simulation in the Dez Basin. Of the 23 initial SWAT input parameters, 14 were identified as the most influential based on T-Stat and P-Value and were selected for calibration

(Table 2). The analysis revealed that the Curve Number (CN2), Baseflow Alpha Factor (ALPHA_BNK), and Effective Hydraulic Conductivity (CH_K2) were the most sensitive parameters governing streamflow in the Dez Basin, which is consistent with the basin's physical characteristics (i.e., high surface runoff contribution and permeable alluvial channels).

Figure 5 compares the monthly simulated streamflow with observed values during the calibration (1986–2005) and validation (2006–2018) periods at the Telezang gaging station. During calibration, the Nash–Sutcliffe efficiency (NSE) and coefficient of determination (R^2) were 0.81 and 0.82, respectively. In the validation period, despite experiencing recurrent droughts, the model demonstrated robust performance with NSE and R^2 values of 0.89 and 0.83, respectively. The Percent Bias (PBIAS) remained within an acceptable range, showing no systematic overestimation or underestimation. According to Moriasi et al. (2007), who classified monthly streamflow simulation NSE values > 0.65 as "good" and > 0.80 as "very good," the SWAT model's performance in both periods is rated as "very good."

Furthermore, simulation uncertainty was evaluated using P-factor and R-factor indices derived from the SUFI-2 algorithm. In the calibration period, the P-factor was 0.74 and the R-factor was 0.8; in the validation period, these values were 0.69 and 0.77, respectively. The confinement of the majority of observed data within the 95% uncertainty band (95PPU), combined with a relatively narrow band width, indicates that the SUFI-2 algorithm effectively controlled parameter uncertainty, providing reliable results for future climate scenario analysis. Optimized values for the calibrated parameters are presented in Table 3.

Table 2. Optimized values for the influential parameters in the SWAT calibration phase

Parameter names*	Description	File	Final value
r__CN2.mgt	curve number	mgt	-0.2-0
v__ALPHA_BNK.rte	Baseflow alpha factor for bank storage (days)	rte	0.05-0.25
v__CH_K2.rte	Effective hydraulic conductivity (mm/hr)	rte	104-122
v__CH_N2.rte	Manning's n value for the main channel	rte	0.1-0.16
v__SFTMP.bsn	Snowfall temperature (°C)	bsn	1.5
v__SMTMP.bsn	Snow melt base temperature (°C)	bsn	3.5
v__RCHRG_DP.gw	Deep aquifer percolation fraction	gw	0.7-0.9
v_CANMX.hru_	Maximum canopy storage (mm)	Hru	79
v__EPCO.hru	Plant uptake compensation factor	hru	0.7-0.9
v__SMFMN.bsn	Melt factor for snow on day of winter solstice	bsn	2.5
v__SLSUBBSN.gw	Average slope length (m)	gw	11.-128
v__GWQMN.gw	Threshold water depth in the shallow aquifer (mm)	gw	600-900
v__GW_REVAP.gw	Groundwater revap coefficient	gw	0.1-0.5
v__ESCO.hru	Soil evaporation compensation factor	hru	0.7-0.9

**r_ means that the existing parameter value is multiplied by (1 + a given value), while v_ means that the default parameter is replaced by a given value.*

3.4. Changes in Streamflow Regime and Flow Duration Curve

Figure 6 presents the projected changes in the Dez River's monthly mean streamflow and flow duration curve (FDC) for a baseline period and three future time slices under both RCP4.5 and RCP8.5 scenarios. These analyses consistently demonstrate that climate change is expected to not only decrease the mean river discharge but also modify the probability distribution of streamflow, consequently diminishing the hydrological reliability of the river system.

During the baseline period, the mean annual streamflow was 249.8 $m^3 s^{-1}$. Under the RCP4.5 scenario, this is projected to decrease to 127.0 $m^3 s^{-1}$ (49.2% reduction) for 2041–2060, 118.6 $m^3 s^{-1}$ (52.5% reduction) for 2061–2080, and 108.0 $m^3 s^{-1}$ (56.8% reduction) for 2081–2100. For the RCP8.5 scenario, the projected

mean annual streamflow are 138.1 $m^3 s^{-1}$ (44.7% reduction), 108.4 $m^3 s^{-1}$ (56.6% reduction), and 89.5 $m^3 s^{-1}$ (64.2% reduction) for the same respective periods. These findings indicate that while streamflow reduction is initially more pronounced under RCP4.5 in the near future, the decline intensifies under RCP8.5 after mid-century, leading to the most significant reduction in river discharge by the end of the century.

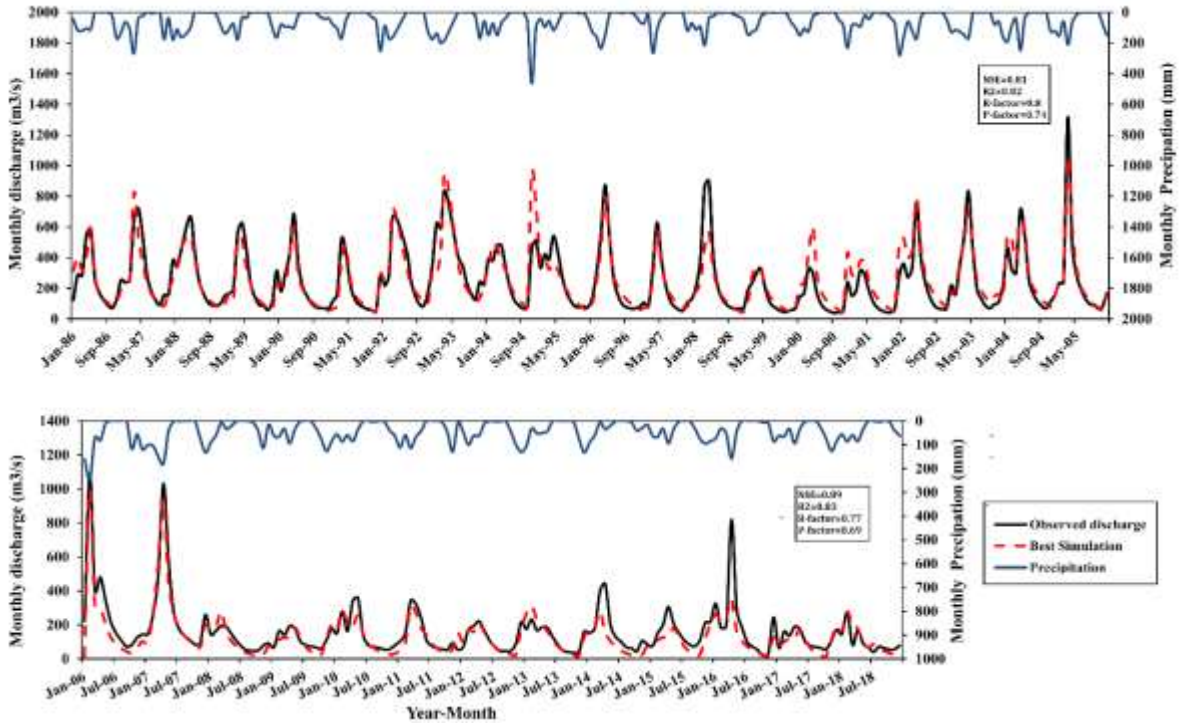


Figure 5. Comparison of observed and SWAT-simulated monthly streamflow during the calibration (1986–2005) and validation (2006–2018) periods, together with the corresponding model performance statistics.

Analysis of the monthly streamflow regime (Figure 6a,b) reveals that the most significant reductions in discharge occur during the wet season. During the baseline period, peak streamflow in April reached approximately 600 $m^3 s^{-1}$. Projections indicate that this peak will decrease to 311, 268, and 244 $m^3 s^{-1}$ under the RCP4.5 scenario, and to 342, 225, and 163 $m^3 s^{-1}$ under the RCP8.5 scenario, for the three respective future periods. These figures represent reductions of approximately 48–59% under RCP4.5 and 43–73% under RCP8.5 compared to the baseline. A substantial decline in streamflow is also projected for March and May, suggesting that the largest reductions in runoff will coincide with the Dez Reservoir's primary recharge season.

A declining trend is also evident during the low-flow season, although its magnitude is smaller than that observed during the wet season. For example, under the RCP4.5 scenario, September streamflow is projected to decrease from 79 $m^3 s^{-1}$ in the baseline period to approximately 63 $m^3 s^{-1}$ by the end of the century. Under the RCP8.5 scenario, this reduction is even more pronounced, with flows dropping to about 50 $m^3 s^{-1}$. Nevertheless, because the majority of the Basin's annual water resources are generated during the wet season, the pronounced reduction in spring streamflow is expected to have a substantially greater impact on reservoir storage than the decline in summer flows.

The flow duration curves (Figure 6c,d) corroborate this pattern. A downward shift in all future flow duration curves signifies a reduced probability of high-flow events and an increased frequency of low-flow conditions. This indicates a decline in the Basin's runoff generation capacity and a greater likelihood of hydrological water scarcity under future climate conditions.

The most significant divergence between the curves appears at lower exceedance probabilities (less than approximately 20%), which correspond to high-flow events. This suggests that climate change will predominantly impact flood and high-flow conditions, resulting in a substantial reduction in peak discharges. Conversely, the differences among the curves diminish at high exceedance probabilities (greater than 80%). This indicates that while baseflows are also projected to decrease, their relative reduction is less pronounced compared to high flows.

Comparison of the two emission scenarios shows that the RCP8.5 curve for the 2081–2100 period consistently occupies the lowest position across the entire range of exceedance probabilities. This indicates simultaneous reductions in high, medium, and low flows. This pattern suggests that continued high greenhouse gas emissions will shift the Dez River's hydrological regime toward persistently lower streamflows, reduced water supply reliability, and a higher frequency of water scarcity conditions.

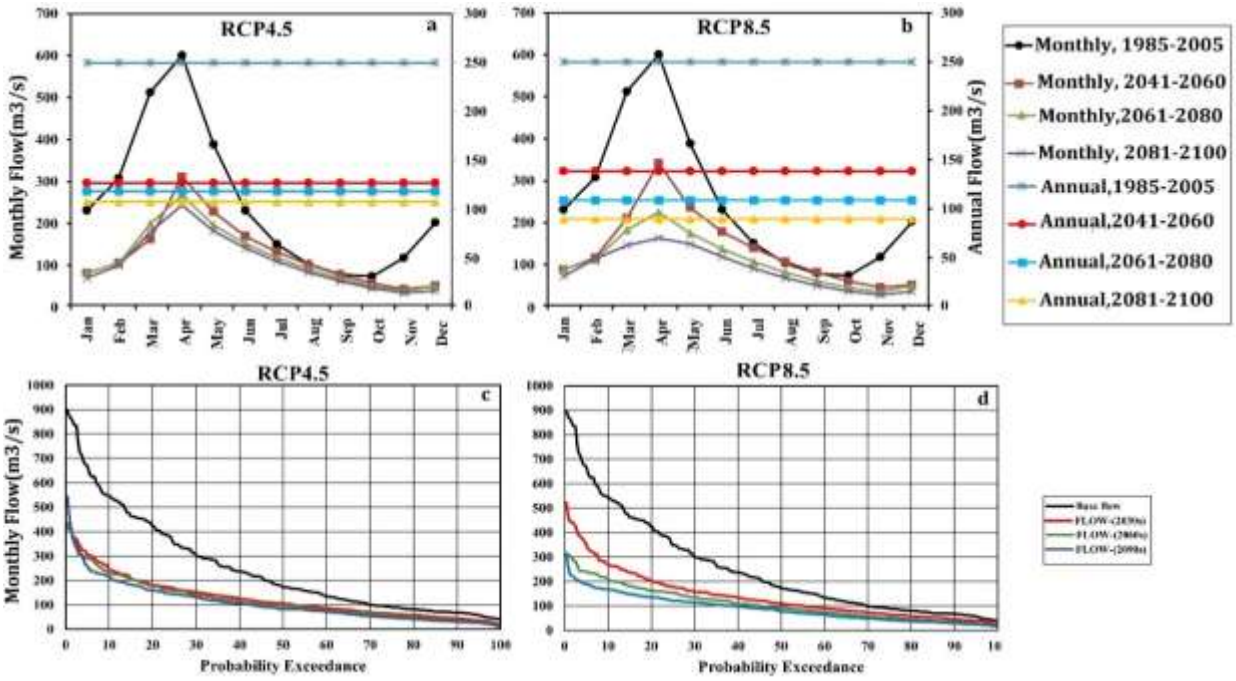


Figure 6. Projected changes in inflow regime and flow duration curves (FDCs) of the Dez Reservoir under the RCP4.5 and RCP8.5 scenarios: (a, b) monthly mean reservoir inflow; (c, d) inflow flow duration curves (FDCs)

3.5. Changes in Reservoir Outflow from the Dez Dam

Figure 7 illustrates the temporal variations in monthly outflow from the Dez Reservoir during the baseline period and three future periods (2041–2060, 2061–2080, and 2081–2100) under the RCP4.5 and RCP8.5 scenarios. For both emission scenarios, the temporal pattern of reservoir outflow demonstrates noticeable changes when compared to the baseline period, specifically a simultaneous reduction in the magnitude of fluctuations and the intensity of peak releases.

During the baseline period, reservoir outflow is highly variable, with several large peaks exceeding 3000 MCM. This indicates periods of high inflow and the potential for releasing considerable volumes of water. In contrast, the magnitude of these peaks decreases considerably in all future periods, with outflow generally fluctuating below 800 MCM. This finding indicates that climate-induced reductions in reservoir inflow have substantially constrained the reservoir's capacity to release water. Under the RCP4.5 scenario (Figure 7a), the seasonal pattern of reservoir outflow is partially maintained, but the range of variations decreases across all three future periods compared to the baseline. The reduction in peak outflow intensity becomes more pronounced from 2081–2100, with reservoir releases remaining at lower levels for most

months compared to the 2041–2060 and 2061–2080 periods. This trend suggests a gradual decline in the reservoir's regulation capacity due to reduced basin inflow.

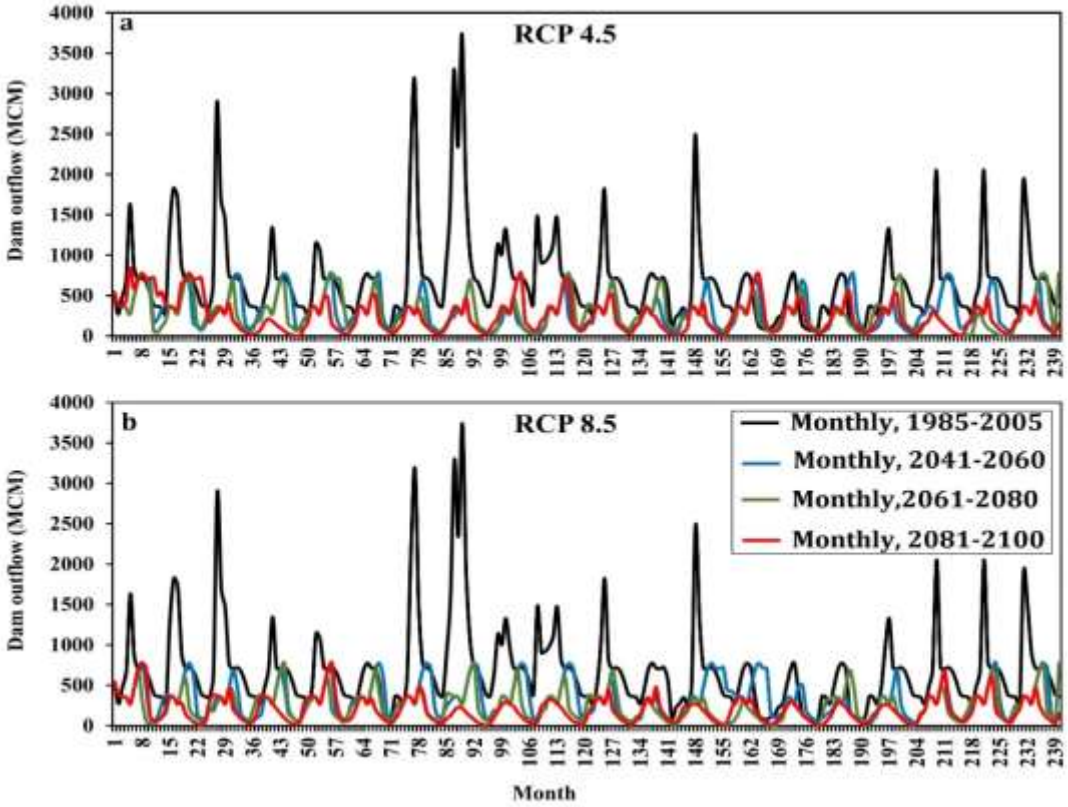


Figure 7. Comparison of monthly reservoir outflow volumes from the Dez Reservoir during the baseline and future periods under the RCP4.5 and RCP8.5 climate change scenarios.

Under the RCP8.5 scenario (Figure 7b), these changes are considerably greater. Peak outflow values are not only significantly reduced, but the variability of reservoir releases also becomes more uniform, narrowing the difference between high-flow and low-flow periods. This indicates that under more severe climate conditions, the reservoir substantially loses its capacity to store and release large volumes of water. During the 2081–2100 period, reservoir outflow remains at its lowest levels for most months, with only a few limited increases during periods of seasonal runoff generation. One of the most important features in the figure is the gradual disappearance of extremely large outflow events *(high-flow* releases). While several high-volume releases occur during the baseline period, these events are nearly eliminated under future climate scenarios. This indicates that climate change not only reduces the mean streamflow volume but also decreases the frequency and magnitude of high-flow events. Many recent studies have identified this as a major impact of climate change on reservoir performance.

Overall, the comparison between the two scenarios indicates that although both result in a reduction in reservoir outflow, the decline occurs more rapidly and intensely under the RCP8.5 scenario. The persistence of this trend until the end of the century could significantly constrain the Dez Reservoir's ability to simultaneously satisfy agricultural, domestic, industrial, and environmental water demands. Therefore, these findings highlight the urgent need to revise reservoir operation rules and develop effective adaptation strategies to cope with future climate conditions.

3.6. Water Demand Satisfaction under Baseline and Climate Change

Table 3 presents the MODSIM model's results for the satisfaction of domestic, industrial, agricultural, and environmental water demands. The environmental flow requirements, fish farming, and Ghadeer domestic

and industrial water demands were fully met from 1986 to 2005, with no observed water shortages. However, the Dezful industrial, Dezful agricultural, Ghadeer agricultural, and Dezful domestic demands experienced water supply deficits in some months during this period.
Despite these monthly shortfalls, both the volumetric and temporal reliability indices remained within the acceptable ranges set by the Ministry of Energy's water allocation regulations. Overall, Ministry of Energy reports indicate that the Dez Reservoir has consistently fulfilled its allocated water rights to date.

Table 3. Annual water demands and water demand satisfaction percentages during the baseline period (1986–2005)

Demand	Demand	Supply (MCM)	Volumetric	Temporal
Shorbe Ghadeer	350	350	100	100
San'ate Ghadeer	100	100	100	100
Environmental	1327	1327	100	100
Dez Agriculture	1000	875	88	89
Dezful Urban Water Supply	102	92	90	90
Dezful Industrial	178	162	91	90
Fish Farming	28	28	100	100
Band- e Qir Agriculture	4035	3701	92	90

Table 4 presents the volumetric and temporal reliability of Dez Reservoir water demands under the RCP4.5 and RCP8.5 scenarios during future periods. The results indicate that Ghadeer's domestic and industrial water demands are fully satisfied in future periods due to their higher priority compared with other water uses.

Table 4. Percentage of water demand supplied by the Dez Dam under RCP4.5 and RCP8.5 scenarios

Demand	Index	RCP4.5			RCP8.5		
		2040s	2060s	2090s	2040s	2060s	2090s
Shorbe Ghadeer	Volumetric Reliability	100	100	100	100	100	100
	Temporal Reliability	100	100	100	100	100	100
San'ate Ghadeer	Volumetric Reliability	100	99	100	100	100	100
	Temporal Reliability	100	99	100	100	100	100
Environmental	Volumetric Reliability	92	78	82	93	84	78
	Temporal Reliability	79	74	69	83	69	64
Dez Agriculture	Volumetric Reliability	22	19	17	28	14	9
	Temporal Reliability	42	38	33	47	34	21
Dezful Urban Water Supply	Volumetric Reliability	39	37	32	47	32	23
	Temporal Reliability	44	41	37	50	37	27
Dezful Industrial	Volumetric Reliability	49	45	39	55	40	29
	Temporal Reliability	44	40	35	49	35	25
Fish Farming	Volumetric Reliability	74	57	39	100	44	24
	Temporal Reliability	95	54	38	95	11	6
Band- e Qir Agriculture	Volumetric Reliability	49	37	32	55	41	30
	Temporal Reliability	44	41	37	51	38	27

The volumetric reliability index for environmental water requirements indicates that demand will be largely met during the near-future period (2040s) under both RCP4.5 and RCP8.5 scenarios. However, water shortages are projected for the mid- and far-future periods. Specifically, the Dez and Band-e Qir agricultural sectors are expected to face the most severe challenges due to future climate conditions, particularly in the latter decades of the 21st century. By the 2090s, the volumetric demand satisfaction rate for Dez agriculture is projected to drop drastically to 17% under RCP4.5 and to merely 9% under RCP8.5 (compared to 22% and 28% in the 2040s, respectively). Similarly, demand satisfaction for Band-e Qir agriculture declines to approximately 26–30%, underscoring the extreme vulnerability of the downstream agricultural sector to climate-induced water shortages.
Table 4 shows that satisfaction rates for Dezful's domestic, industrial, and fish farming water demands fall below standard thresholds set by water allocation regulations. The only exception is fish farming demand

during the 2040s under the RCP8.5 scenario. Furthermore, by the end of the century, demand satisfaction percentages decline to less than 39% under the RCP4.5 scenario and below 30% under the RCP8.5 scenario, indicating increased water stress in the region.

4. Discussion

This study identifies the reduction in Dez River streamflow as the most significant hydrological consequence of climate change under future climate scenarios. This decline is considerably more pronounced than the direct reduction in precipitation. Despite an approximately 17–18% decrease in annual precipitation by the end of the century under the pessimistic RCP8.5 scenario, the Dez River's mean annual streamflow is projected to decline by more than 60%. This nonlinear response indicates that streamflow changes are not solely controlled by precipitation variations but are also influenced by the rainfall–runoff transformation process. This process is affected by increased temperature, enhanced evapotranspiration, reduced soil moisture availability, altered snowmelt processes in mountainous regions, and a decline in effective precipitation. Similar responses have been reported in mountainous basins, where previous studies have demonstrated that rising temperatures can amplify the impacts of precipitation reduction on runoff, leading to future streamflow declines of a substantially greater magnitude than precipitation decreases (Motiee et al., 2026).

A comparative analysis between the intermediate scenario (RCP4.5) and the pessimistic scenario (RCP8.5) reveals fundamental differences in the magnitude, nonlinearity, and underlying mechanisms of hydrological changes in the Dez Basin. While streamflow experiences a severe and disproportionate contraction (exceeding 60%) under the pessimistic RCP8.5 scenario, the reduction under RCP4.5 remains considerably more moderate, demonstrating that global mitigation and climate stabilization efforts can effectively prevent the catastrophic loss of surface water resources. This divergence is primarily driven by thermal amplification and snow-dynamic feedbacks rather than precipitation changes alone. Under RCP4.5, milder temperature increases preserve a significant portion of the high-altitude snowpack, thereby maintaining essential baseflows into late spring. In contrast, under the pessimistic RCP8.5 scenario, excessive thermal forcing accelerates the shift from snowfall to rainfall and induces premature, flashier snowmelt during late winter, leaving insufficient snowpack storage to sustain spring and early-summer flows. Furthermore, the intensified atmospheric evaporative demand under the pessimistic RCP8.5 scenario severely exacerbates soil moisture deficits, requiring a much larger fraction of rainfall to satisfy antecedent soil saturation before effective runoff can be generated; this desiccation feedback is far less severe under RCP4.5.

The present findings in the Dez Basin align with those of Mousavi (2017), whose SWAT model study on climate change impacts on hydrological processes in the basin revealed that future climate changes could diminish surface runoff and alter water balance components. Similarly, Asgari et al. (2024) demonstrated that climate change could substantially reduce inflow to the Dez Reservoir, consequently decreasing energy production capacity and limiting reservoir performance. The present study extends previous findings by demonstrating that reduced reservoir inflow not only affects hydropower generation but can also compromise the multi-purpose operational performance of the Dez Reservoir in meeting downstream water demands.

The varying magnitudes of streamflow reduction across different months indicate that the system's greatest vulnerability will occur during the wet season, particularly from March to May. The substantial decline in peak discharge during April is especially critical because this period plays a vital role in reservoir filling and generating storage reserves for low-flow months. Therefore, a reduction in spring streamflow will not only decrease the total annual inflow volume but also alter the timing of water availability to the reservoir, thereby limiting the flexibility of reservoir operation Recent studies on reservoir management have also demonstrated that changes in the timing of inflow can decrease the reliability of water supply systems, even with moderate reductions in annual water volume. This is because conventional operating rules are typically developed based on historical and relatively stable flow regimes, which may become less effective under future climate conditions (Dash et al., 2023).

Flow duration curves further demonstrate that climate change in the Dez Basin will likely reduce the probability of high-flow events while increasing the frequency of low-flow conditions. This shift is particularly significant for multipurpose reservoirs. High-flow periods are crucial not only for replenishing reservoir storage but also for providing greater flexibility in balancing competing demands, such as those for agriculture, domestic use, and environmental needs. A reduction in these flows could intensify competition among various water users and constrain reservoir managers' ability to effectively respond to fluctuating demands. Recent studies in other regions have also shown that climate change can reduce reservoir reliability and necessitate revisions to operational strategies. For example, a study of a water supply reservoir in Brazil reported a substantial decline in reliability under future climate scenarios, demonstrating that modified operation rules and adaptation measures are essential for maintaining reservoir performance (Chaves et al., 2023).

Reduced outflow from the Dez Reservoir in the future will be a direct consequence of decreased natural inflows and the reservoir's limited regulatory capacity. The gradual disappearance of high-volume release events in future scenarios indicates that, under more severe climatic conditions, the reservoir will have fewer opportunities to store water during wet years and meet water demands during dry periods. This issue is particularly critical for large reservoirs in arid and semi-arid regions, where even relatively small changes in inflow can substantially affect the balance between water supply and demand. Recent studies have demonstrated that combining hydrological models, such as SWAT, with reservoir operation models offers an effective framework for assessing uncertainties and developing climate-adaptive operational strategies for future conditions (Singson et al., 2023).

Results from the MODSIM model indicated that reduced reservoir inflow will ultimately diminish the Dez Reservoir's capacity to meet certain downstream water demands. Comparing the operational trajectories under RCP4.5 and the pessimistic RCP8.5 scenario highlights marked differences in system vulnerability and adaptive capacity. Under RCP4.5, although operational reliability slightly declines during seasonal dry spells, the reservoir maintains sufficient regulatory buffer to satisfy domestic, municipal, and primary agricultural demands through optimized rule curves and dynamic release policies. Under the pessimistic RCP8.5 scenario, however, prolonged and severe inflow deficits breach critical operating thresholds, triggering structural supply failures. While high-priority domestic and industrial demands maintain relatively high reliability due to strict allocation hierarchies, agricultural water allocations experience acute deficits, and environmental downstream flows are severely compromised or entirely omitted during extended droughts to safeguard municipal supplies. Therefore, the transition from the RCP4.5 scenario to the pessimistic RCP8.5 scenario does not merely represent a linear decrease in water yield but indicates a qualitative threshold where reservoir operation shifts from an adaptable regime to an acute water-stress crisis.

This finding is consistent with studies on other Iranian reservoirs, such as the Maroon Reservoir. For instance, an integrated SWAT–MODSIM modeling framework revealed that pessimistic (high-emission) scenarios could reduce reservoir inflow, thereby decreasing water supply reliability and intensifying water stress (Mirmehdi et al., 2023).

5. Conclusion

This study evaluated the operational performance of the Dez Reservoir in satisfying downstream water demands under future climate change conditions. An integrated framework, comprising climate models, the SWAT hydrological model, and the MODSIM water allocation model, was used for this purpose. Outputs from five general circulation models (CMIP5) under the RCP4.5 and RCP8.5 emission scenarios were downscaled and combined to simulate future climate conditions. The impacts of these changes on reservoir inflow, reservoir performance, and the satisfaction of various downstream water demands were subsequently assessed.

Climate model projections for the Dez Basin indicated a future marked by declining annual precipitation and substantial increases in both minimum and maximum temperatures. By the end of the century, annual precipitation is projected to decrease by 17.2% to 18.0%. These climatic shifts are projected to significantly

reduce inflow to the Dez Reservoir. Specifically, mean annual streamflow is anticipated to decrease by 49.2–56.8% under the RCP4.5 scenario and by 44.7–64.2% under the RCP8.5 scenario, when compared to baseline periods.

The assessment of Dez Reservoir performance showed that reduced reservoir inflow will decrease both the volume and variability of its outflow in future periods. Although both climate scenarios indicated a decline in performance, the reduction was greater under the RCP8.5 scenario, leading to more severe operational constraints by the end of the century. Furthermore, the MODSIM model results demonstrated that climate change does not affect all downstream water uses equally. High-priority demands, such as domestic water supply and Ghadeer industrial demand, will maintain higher satisfaction levels, whereas agricultural, environmental, and some downstream water demands will experience substantial reductions in demand satisfaction during future periods.

The findings of this study indicate that climate change may diminish the Dez Reservoir's operational reliability in simultaneously fulfilling its multi-objective water requirements, including those for agricultural, domestic, industrial, and environmental uses. Consequently, continuing to operate the Dez Reservoir system based on historical water allocation patterns will be insufficient under future climate conditions; thus, adopting climate-adaptive management approaches is essential.

Significant improvements to the resilience of the Dez Basin's water resources system can be achieved by enhancing water consumption patterns, increasing agricultural water-use efficiency, revising water allocation policies, implementing modern irrigation technologies, and developing adaptive reservoir operation strategies. Despite the satisfactory performance of the models used in this study, several uncertainties remain. The primary limitations of this research include the use of a limited number of climate models, the assumption of constant future land-use conditions and water demands, and the exclusion of potential changes in reservoir operation policies. Therefore, future studies should investigate the combined effects of climate change, land-use alterations, variations in water demand, and alternative reservoir operation strategies. These studies should incorporate more recent climate models and adaptive management approaches to provide a more comprehensive assessment of future water resource conditions in the Dez Basin.

Authors' Contributions

All authors contributed to the conceptualization, methodology, investigation, writing, and editing of this manuscript.

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Data Availability Statement

The GCM outputs used in this study are publicly available from the CMIP5 archive through the Earth System Grid Federation (ESGF). Observed meteorological data were obtained from the Iran Meteorological Organization (IRIMO), and hydrometric, reservoir operation, and water-demand data were obtained from the Khuzestan Water and Power Authority (KWPA). These data are subject to institutional restrictions and are available from the corresponding author upon reasonable request and with permission of the respective organizations.

Declaration of AI Use

The authors used AI-based language tools to improve the language, clarity, and readability of the manuscript. All scientific content, interpretations, and conclusions are solely the responsibility of the authors.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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