The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 36, Pages 174-182

ICBAST 2025: International Conference on Basic Sciences and Technology

Quantifying Uncertainty in Projected Temporal Variations of Reservoir Releases for Crop Water Requirement

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Abstract: Climate change brings about significant uncertainties in reservoir operation and agricultural water management. This study aims to assess the temporal variability and associated uncertainties in reservoir release projections to meet the agricultural water demand for maize in the Beydag Reservoir, located in İzmir, Türkiye. Agricultural water demand was estimated based on the FAO Penman-Monteith potential evapotranspiration method, employing crop-specific coefficients for maize. Reservoir operation was carried out by means of the Standard Operating Policy (SOP). Future runoff projections were derived from a 140-member ensemble constructed by combining five general circulation models (GCMs), two emission scenarios (RCP4.5 and RCP8.5), two downscaling methods (statistical and dynamical), and seven calibrated hydrological models. Using these projections, annual reservoir releases under SOP were simulated and evaluated in terms of anomalies relative to a historical baseline. Uncertainty analysis based on variance decomposition revealed that GCMs exert a rather dominant influence on total projection uncertainty in reservoir releases. Moreover, the SOP approach demonstrated limited responsiveness to the increasing temporal variability imposed by climate change because it prioritizes meeting current demand without reserving water for future use. The results emphasize the critical need to consider uncertainty assessments for the planning of water-sensitive cropping strategies such as maize cultivation.

Keywords: Reservoir operation, Agricultural water management, Standard operating policy, Beydag reservoir

Introduction

In recent decades, climate change has increasingly emerged as a major challenge for water resources management. Rising air temperatures, altered precipitation regimes, and the greater frequency of extreme events such as droughts and floods have already begun to reshape hydrological systems worldwide. According to the IPCC Sixth Assessment Report (2021), these impacts are especially pronounced in semi-arid and Mediterranean-type climates, where water availability is already under stress. These conditions directly influence reservoir management, as the long-standing assumption of hydrological stationarity can no longer be considered valid. Reservoirs that were originally designed and operated on the basis of historical inflows are now confronted with greater variability and uncertainty, which significantly constrains their capacity to satisfy multiple and often competing water demands (Raje & Mujumdar, 2010).

The Standard Operating Policy (SOP) is often used as a benchmark in reservoir studies due to its straightforward structure, which allocates available inflows to meet current demands without explicit provision for future shortages. Owing to this simplicity, SOP is frequently taken as a reference in reservoir operation studies and compared against more advanced alternatives such as hedging strategies, dynamic rule curves, or optimization-based approaches (Ashofteh et al., 2013; Hakami-Kermani et al., 2020). However, although SOP may provide acceptable performance under stationary inflows, several studies have indicated that its rigid nature becomes inadequate under increased variability, resulting in reduced reliability and greater vulnerability during extended droughts (Ashofteh et al., 2013; Hakami-Kermani et al., 2020).

Agriculture, which consumes nearly 70% of global freshwater withdrawals (FAO, 2021), is highly exposed to the effects of climate change. Changes in climate tend to place more pressure on irrigation over time. Recent studies of semi-arid basins show irrigation demand rising by about 10% in some cases (Hakami-Kermani et al., 2020) and close to 40% in others, depending on crop pattern and scenario (Golfam et al., 2025). In regions such as Iran, wheat, maize, and alfalfa are projected to require considerably more irrigation under future climates (Ashofteh et al., 2013; Ashofteh et al., 2015). Comparable challenges are already evident in western Türkiye, where agriculture accounts for the largest share of water use. Among major crops, maize is especially sensitive to water shortages. Both experimental and modeling studies confirm that irrigation deficits during critical stages—particularly flowering and grain filling-can cut yields by 30–50% or more (Meza et al., 2008; Kim & Lee, 2023). Even short interruptions in irrigation may translate into substantial economic losses. This makes dependable reservoir releases essential to sustain maize production under warmer and drier conditions.

Projecting how reservoirs will perform under future conditions is complicated by multiple sources of uncertainty. Among them, differences across general circulation models (GCMs) usually dominate, often exceeding the effects of emission scenarios or the choice of hydrological model (Her et al., 2019; Nkomozepi & Chung, 2012). Additional variation is introduced through downscaling methods, while natural climate variability makes long-term planning even more difficult. Previous ensemble-based studies have shown that these layers of uncertainty directly influence key performance measures such as reliability, resilience, and vulnerability (Ashofteh et al., 2013; Ashofteh et al., 2015).

This study focuses on the Beydag Reservoir in western Türkiye to provide such an assessment. The analysis has two main objectives: (i) evaluating temporal anomalies in reservoir releases for maize irrigation under SOP relative to a historical baseline, and (ii) quantifying the contributions of GCMs, emission scenarios, downscaling approaches, and hydrological models for projection uncertainty through variance decomposition. The study offers a basis for understanding how SOP performs under changing inflow conditions and emphasizes the importance of incorporating uncertainty into planning to ensure reliable irrigation for water-intensive crops such as maize.

Data Used

Study Region and Observed Data

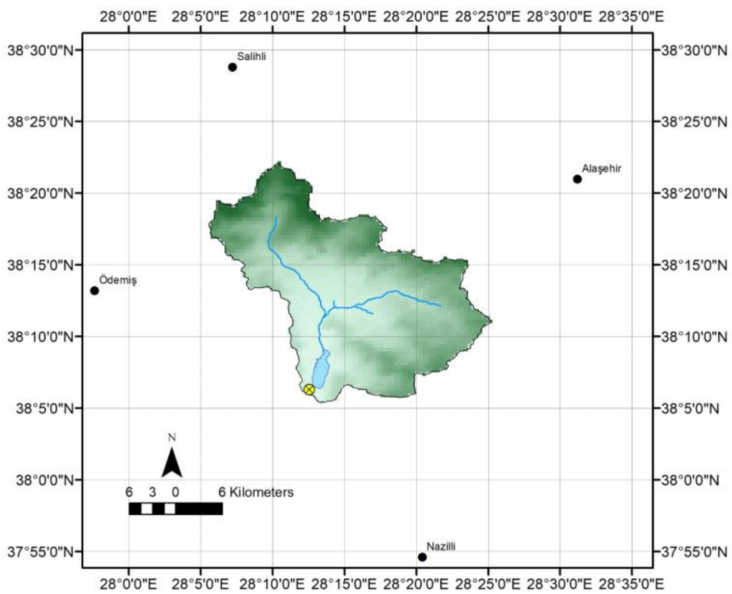

Figure 1. Location and drainage area of the Beydag Reservoir catchment.

The Beydag watershed, covering about 445 km², lies in the Kucuk Menderes Basin of western Türkiye and was selected as the study area. The basin hosts the Beydag Reservoir, a structure with nearly 243 Mm³ of active storage capacity that ensures irrigation supply. Maize stands out as the principal crop within the irrigation scheme, shaping both the seasonal demand pattern and the overall reservoir operation.

To reflect natural conditions, streamflow records from 1987 to 1999 were combined with reservoir characteristics, including storage–area curves supplied by the State Hydraulic Works. During this period, the watershed received an average of 485 mm of annual precipitation, while mean temperature was about 16 °C. Runoff was limited to roughly 95 mm per year-around one-fifth of the precipitation-indicating the semi-arid climate and the water-stressed character of the basin (Ersoy et al., 2025a).

Local Projected Climate Data

Future hydro-climatic conditions in the Beydag watershed were examined through a modeling framework that incorporated five global climate models (GCMs), two emission scenarios (RCP4.5 and RCP8.5), and both statistical and dynamical downscaling approaches. When combined with seven lumped hydrological models, this chain produced 140 alternative runoff projections (Ersoy et al., 2025b). These data were then formed the basis for analysis under SOP.

For the dynamical simulations, climate data were compiled from the CORDEX–MENA archive, covering the baseline period 1981–2005 together with four projection horizons: 2021–2039, 2040–2059, 2060–2079, and 2080–2099. Outputs from five GCMs (CNRM-CM5, GFDL-ESM2M, EC-EARTH, HadGEM2-ES, and MPI-ESM-MR) were available for both RCP4.5 and RCP8.5. Bias adjustment was conducted using the quantile delta mapping (QDM) method, which ensures the preservation of relative changes. According to the corrected CORDEX results, precipitation anomalies under RCP4.5 were generally negligible, whereas under RCP8.5 certain members, such as GFDL-CRX and EC-EARTH-CRX, indicated substantial reductions after the 2060s. Conversely, HadGEM-CRX suggested increases in late-century precipitation. Temperature projections displayed a consistent warming pattern across all models, with end-of-century anomalies between 1.0–2.0 °C for RCP4.5 and 3.4–6.9 °C for RCP8.5. HadGEM-CRX produced the strongest warming, in line with earlier findings over the MENA domain (Ozturk et al., 2021).

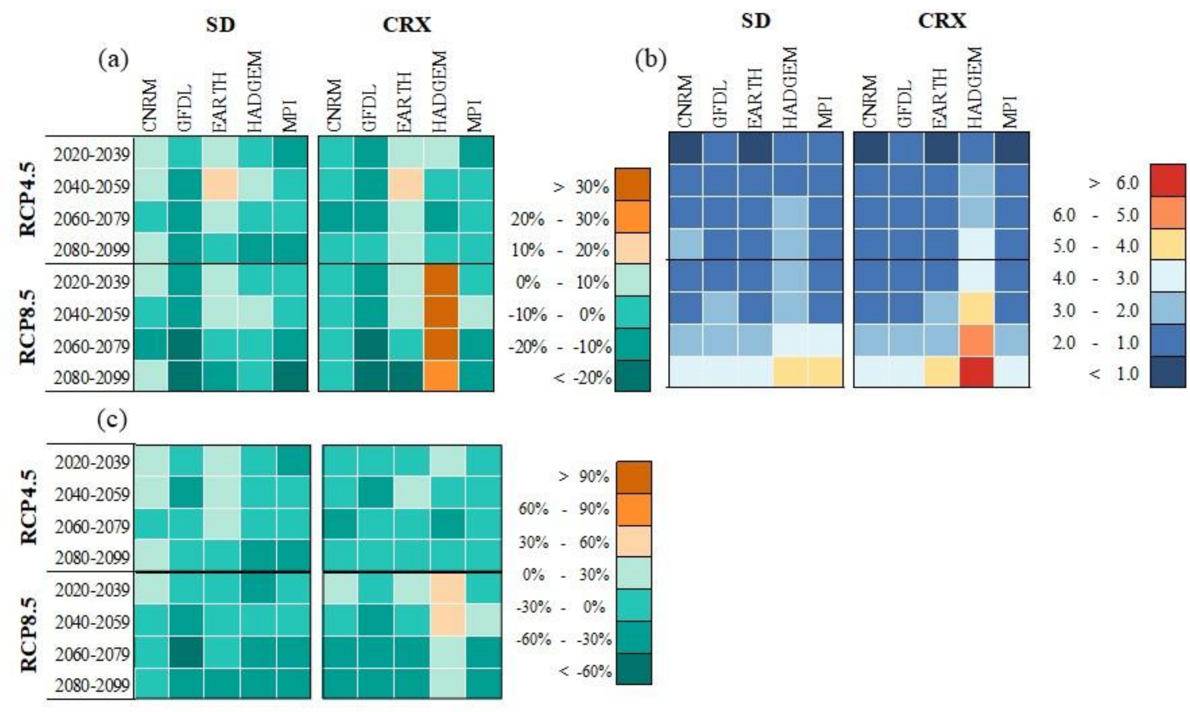

Figure 2. Hydroclimatic anomalies in the Beydag basin under RCP4.5 and RCP8.5 scenarios for five GCMs and two downscaling methods: (a) precipitation (%), (b) temperature (°C), (c) streamflow (%).

Statistical downscaling relied on radial basis function networks (RBFNs), where predictor variables were selected through the LASSO method. Model evaluation showed reliable skill, as NSE values exceeded 0.75 in both calibration and validation. The resulting data were bias corrected with QDM before analysis. The precipitation signals obtained were broadly aligned with those from CORDEX, showing only minor deviations. For temperature, HadGEM-SD indicated stronger warming under RCP8.5 compared with most models, although its anomalies were still 1.5–2.5 °C lower than HadGEM-CRX. This pattern suggests that part of the amplified signal in CORDEX outputs may originate from RCM parameterization effects (García-Díez et al., 2015). Overall, both downscaling approaches pointed to robust warming, whereas precipitation projections remained more uncertain and largely governed by GCM selection.

Ensemble of Hydrological Projections

Seven lumped rainfall–runoff models (abcde, AWBM, Dynwbm, Gr2m, Guo, Témez, and Twbm) formed the hydrological basis of this study. These models had been calibrated through global optimization techniques and assessed in earlier applications (Ersoy et al., 2025a). Their structure requires only monthly precipitation and potential evapotranspiration inputs. Calibration and validation tests yielded NSE scores mostly above 0.65, a range commonly regarded as good to very good. Nonetheless, the relatively short span of naturalized streamflow observations limited their ability to fully capture long-term variability.

Based on these models, 140 runoff projection members were produced, and their twenty-year mean changes (ΔQ) were evaluated against the historical reference. For clarity, Figure 2c presents the ensemble mean across the seven hydrological models. The analysis showed that runoff was highly sensitive: even minor declines in rainfall resulted in considerable decreases in ΔQ. Under RCP8.5, severe drying signals from GFDL led to reductions of 33–74% after 2060. In contrast, HadGEM-CRX produced wetter outcomes in line with its precipitation anomalies, while HadGEM-SD indicated more moderate declines of about −18% to −38%. Among the ensemble, GFDL generated the largest share of statistically significant declines. MPI showed notable changes in almost two-thirds of its projections, whereas CNRM produced significant reductions in roughly 40% of its variants. Overall, the analysis shows that the behavior of runoff projections is largely shaped by the choice of GCMs, RCPs, and HMs, consistent with the inferences of Wang et al. (2020).

Method

Estimate of Water Demand Volume in Reservoir Downstream

Agricultural water demand was estimated through the net water requirement (WR), which is defined as the difference between monthly crop evapotranspiration (Etc) and effective precipitation (Peff).
Crop evapotranspiration was estimated by the following equation:

$$ETc_t = Kc_t \times ETo_t \tag{1}$$

where Kc_t denotes the crop coefficient specific to maize, and ETo_t represents the reference evapotranspiration. Reference evapotranspiration (ETo) could not be directly estimated using the Penman–Monteith (P–M) equation due to data limitations. Instead, the Hargreaves–Samani (H–S) equation was applied, after calibrating its parameters with observed P–M estimates. Calibration with observations from the 1996–2006 period yielded a Nash–Sutcliffe efficiency (NSE) greater than 0.95. This approach was subsequently adopted, together with both CORDEX and statistically downscaled GCM temperature projections, as the basis for deriving PET projections.
Effective precipitation (Peff) was calculated from monthly total precipitation (P) using the SCS method:

$$Peff_t = \begin{cases} \frac{P_t}{125}(125 - 0.2P_t), & P_t \leq 250\ mm \\ 125 + 0.1P_t, & P_t \leq 250\ mm \end{cases} \tag{2}$$

Subsequently, the net water requirement was derived from the following equation:

$$WR_t = ETc_t - Peff_t \tag{3}$$

At the final stage, the calculated WR values were multiplied by the irrigated area (A) to derive the monthly volumetric water demand (Vt):

$$V_t = WR_t \times A \tag{4}$$

Reservoir Operation Policy

One of the most fundamental methods used in reservoir operation is the Standard Operating Policy (SOP). The main principle of this approach is to fully meet the demand of the current period. The water stored in the reservoir is released together with the inflow directly to meet the agricultural demand, without any restriction or conservation for subsequent periods. The mathematical formulation of SOP relies on the principle of mass conservation. The reservoir water budget can be expressed as follows:

$$V_{t+1} = V_t + Q_t - RLS_t - E_t \tag{5}$$

where V_t is the reservoir storage, Q_t is the inflow during period t, RLS_t is the reservoir release for month index t, and E_t is the evaporation loss. The operation constraints are defined as follows:

$$0 \leq RLS_t \leq D_t, \qquad V_{min} \leq V_t \leq V_{mak} \tag{6}$$

where D_t is the agricultural water demand, and V_{min} and V_{mak} are the minimum and maximum storage capacities of the reservoir. In the SOP approach, the release rule is given as:

$$RLS_t = \min\,(D_t, V_t + Q_t - E_t) \tag{7}$$

Accordingly, in each period the water demand is satisfied by considering the available storage together with the inflow. If the demand can be fully met, then $RLS_t = D_t$; otherwise, the release is limited to the maximum amount permitted by the available storage and inflow. In this study, streamflow projections for the Beydag Reservoir were operated under the SOP approach, and the monthly releases (RLS) were computed. The resulting values were then evaluated relative to the historical period to assess future changes.

Uncertainty Analysis

In this study, Variance Decomposition Analysis (VDA) was applied to evaluate the uncertainties in future reservoir release projections. The method considered four key components of the modeling chain: emission scenario (RCP), global climate model (GCM), downscaling method (DM), and hydrological model (HM). Each of these factors was examined using a 140-member ensemble generated from the combination of 5 GCMs × 2 RCPs × 2 DMs × 7 HMs, thereby quantifying the relative contributions of each factor and their interactions to the total uncertainty. The analyses were conducted separately for four future periods (2021–2039, 2040–2059, 2060–2079, 2080–2099) with respect to the historical baseline.

Results and Discussion

Changes in Reservoir Releases

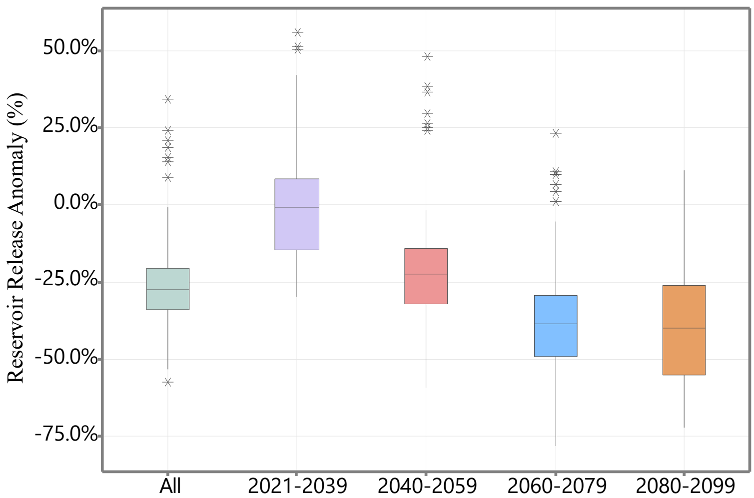

Figure 3. Periodic distributions of changes (%) in reservoir releases under SOP (2021–2039, 2040–2059, 2060–2079, 2080–2099) and for the entire projection period.

Reservoir releases (RLS) from the Beydag Dam under the Standard Operating Policy (SOP) exhibit clear fluctuations throughout the 2021–2099 period relative to the reference baseline. As illustrated in Figure 3, the long-term averages point to a generally declining trend, with some projections indicating reductions of more than 25% and, in the most extreme cases, losses reaching up to 75%. Nevertheless, a few GCMs projected positive anomalies, indicating that under certain conditions RLS could increase.

From a temporal perspective, changes were rather modest in 2021–2039, with some GCMs suggesting minor increases while others indicated slight decreases (Figure 4). The decline became more pronounced during 2040–2059, approaching nearly 25%. From 2060–2079, negative variations continued further while the range in between GCMs increased. By 2080–2099, the most severe reductions were projected, with some models estimating decreases in reservoir releases of up to 75%.

GCM-based results further clarify the direction and magnitude of RLS anomalies. The HadGEM projected comparatively strong increases in precipitation and runoff for the Beydag basin (Ersoy et al., 2025b), which explains the positive outliers in RLS. In contrast, the GFDL yielded the most pessimistic results, indicating streamflow declines of 33–74% and corresponding RLS reductions of up to 75%. MPI tended to project decreases, whereas CNRM suggested more moderate shifts with limited variation

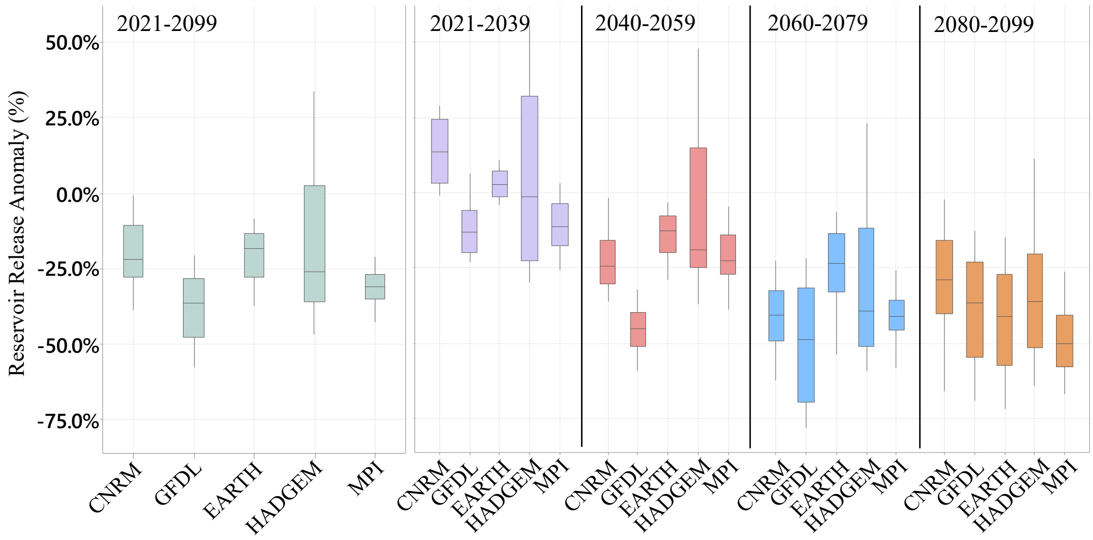

Figure 4. Boxplots of percentage changes in reservoir releases under SOP across five GCMs

These findings suggest that variations in RLS are primarily shaped by projected streamflow changes, along with the added demand pressure from rising temperatures. Under the RCP8.5 scenario, especially during 2080–2099, temperature increases of +3.4 to +6.9 °C are expected to boost evapotranspiration and, in turn, agricultural water demand. As a result, even when flow conditions remain comparable, the heightened demand places additional downward pressure on RLS. Consequently, the Beydag Reservoir is expected to face a pronounced declining trend shaped by the combined effects of climate change on both supply (streamflow) and demand (temperature/evapotranspiration).

Uncertainty Contributions

ANOVA results, used to identify the main sources of variability in RLS projections, show that the largest share of uncertainty arises from GCM selection. As shown in Figure 5, about one-third (30–40%) of the total variance is linked to the choice of GCM. The contribution of emission scenarios (RCPs) remained more limited (5–10%), while hydrological models (HMs) and downscaling methods (DMs) explained only 1–4%. Yet, interactions between GCMs and RCPs made up around 20–25% of the variance, pointing to the key role of model–scenario combinations in shaping the results. Overall, total interactions (TINT) exceeded 50%, making clear that climate-related factors play the biggest role in driving uncertainty in RLS projections.

The temporal evolution of uncertainties is presented in Table 1. While the influence of GCMs was more pronounced in 2021–2039, GCM–RCP interactions grew steadily after 2040 and reached levels comparable to GCM contributions. The contribution of RCPs also grew considerably in the late period. By contrast, the effects of HM and DM selections remained minor across all periods.

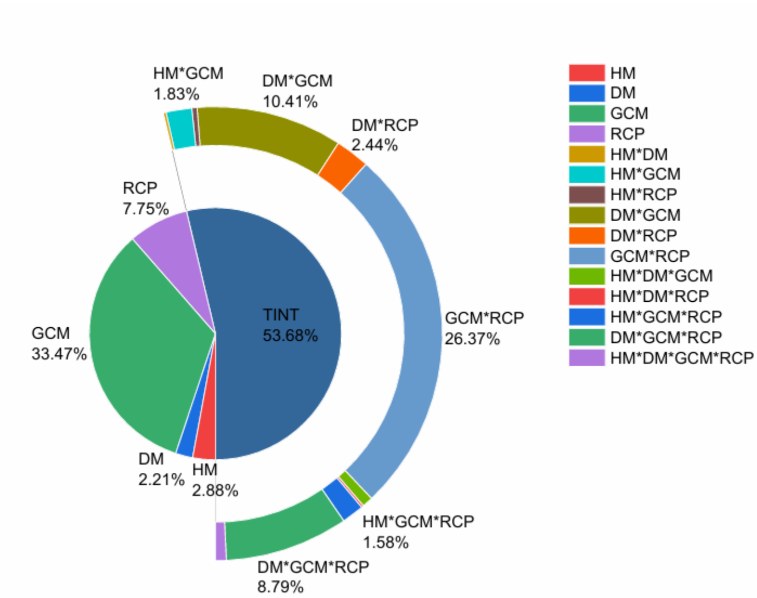

Figure 5. Variance decomposition of reservoir release anomalies (%) under SOP. The inner ring presents the main effects, while the outer ring illustrates the two- and three-way interactions.

Table 1. Variance decomposition (%) of reservoir release anomalies under SOP for four future periods relative to the historical baseline.

	HM	DM	GCM	RCP	GCM*RCP	TINT
2021-2039	4.2%	2.7%	32.9%	5.2%	22.1%	55.0%
2040-2059	1.4%	2.0%	39.3%	6.5%	26.0%	50.8%
2060-2079	3.4%	2.5%	29.7%	9.9%	26.0%	54.5%
2080-2099	2.6%	1.6%	32.0%	9.2%	31.2%	54.5%

The findings show that RLS uncertainties are closely linked to hydroclimatic projections. GCMs stand out as the main source of uncertainty in temperature projections (40–55%), whereas the influence of RCPs becomes more evident by 2080–2099 (Ersoy et al., 2025b). The same tendency is reflected in RLS, where the role of emission scenarios gradually increases in the later periods. Similarly, while GCM–RCP interactions account for 25–30% of the total variance in streamflow projections, their contribution of 20–25% in RLS uncertainties reflects a parallel structure. Hence, RLS uncertainties essentially represent a manifestation of the uncertainties embedded in streamflow and temperature projections: flow-related uncertainties are directly transmitted to RLS, while temperature-driven uncertainties amplify variability in RLS through increased agricultural demand.

Conclusion

In this study, the influence of climate change on reservoir releases for maize irrigation under the Standard Operating Policy (SOP) was assessed. A broad set of hydroclimatic projections was used to capture a wide range of possible futures. The findings show that releases are very sensitive to changing conditions. In the early decades, the impacts remain moderate, but after mid-century the declines become much sharper. Some scenarios even point to reductions exceeding 70% by the end of the century. Such results illustrate the rigid nature of SOP: it can satisfy present demands but offers little room to adjust when inflows vary more strongly. Because maize requires large amounts of water, it is highly vulnerable, and such reductions threaten the sustainability of irrigation.

The uncertainty analysis reveals that global climate models are the leading source of variation in release projections, and their interaction with emission scenarios further amplifies this effect. Although hydrological models and downscaling methods play only a minor role, the dominant effect of climate-related factors shows that uncertainty must be explicitly addressed in future water management. To secure agricultural water supplies, it will be essential to move beyond conventional rules with adaptive strategies that explicitly account for uncertainty.

Scientific Ethics Declaration

*The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

*The authors declare that they have no conflicts of interest

Funding

*This study is funded by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under Grant No. 122Y083.

Acknowledgements or Notes

*The authors gratefully acknowledge the support provided by TÜBİTAK during the course of this research.

*This article was presented as an oral presentation at the International Conference on Basic Sciences and Technology (www.icbast.net) held in Budapest/Hungary on August 28-31, 2025.

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To cite this article:

Ersoy, Z. B., Fistikoglu, O., & Okkan, U. (2025). Quantifying uncertainty in projected temporal variations of reservoir releases for crop water requirement. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 36,* 174-182.