Journal of Hydrology: Regional Studies 59 (2025) 102371

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Future water resources and droughts in the Atlas Mountains of Morocco under a high-emission climate scenario

Ouiaam Lahnik [a], Yves Tramblay [b,*], Lahoucine Hanich [a,c], Jafet C.M. Andersson [d], Redouane Lguensat [e], Kristina Isberg [d], Aicha Ben Ahmed [b], Joel Dahn [d], Benjamin Sultan [b]

[a] *Laboratory of Georesources, Geoenvironment and Civil Engineering (L3G), Cadi Ayyad University, Marrakech, Morocco*
[b] *Espace-Dev, Univ. Montpellier, IRD, Montpellier, France*
[c] *Mohammed VI Polytechnic University (UM6P), Geology and Sustainable Mining Institute (GSMI), Morocco*
[d] *Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden*
[e] *Institut Pierre-Simon Laplace, IRD, Paris, France*

ARTICLE INFO

Keywords:
Climate change impacts
Hydrological modeling
Mountainous region
Drought analysis
Streamflow projection

ABSTRACT

Study Region: Morocco, North Africa. This study examines 36 mountainous basins that supply most of the country's surface water.

Study Focus: This study aims to evaluate the potential impacts of climate change on discharge in Morocco. Two hydrological models, World Wide HYPE and GR4J-CemaNeige, were used in combination with outputs from nine bias-corrected regional climate models. Future discharge was projected under the high-emission RCP8.5 scenario for the mid-century (2040–2060) and late-century (2070–2100). By implementing a state-of-the-art modeling approach on numerous representative sites, the study provides a robust framework for assessing changes in hydrological processes and water availability.

New Hydrological Insights for the Region: This research identifies critical changes in snow dynamics, with peak snow storage projected to decrease by over 50 % due to rising temperatures. Consequently, the contribution of snowmelt to discharge will significantly diminish. These snow-related shifts are heading to an average reduction in discharge of −55 % by the late century (2070–2100). This reduction is primarily driven by significant decreases in precipitation (up to −43 %) combined with substantial increases in potential evapotranspiration (up to +38 %). Additionally, hydrological droughts are expected to become more frequent and prolonged, underscoring the urgent need for adaptive water management strategies specifically designed to address basin-specific characteristics.

1. Introduction

Climate change is one of the most pressing challenges of the twenty-first century, significantly impacting natural cycles, particularly the hydrological cycle. Alterations in precipitation and temperature patterns driven by climate change have spurred extensive research on their effects on global water resources. These shifts disrupt established hydrological regimes across diverse ecosystems

* Corresponding author.
E-mail address: yves.tramblay@ird.fr (Y. Tramblay).

https://doi.org/10.1016/j.ejrh.2025.102371
Received 3 February 2025; Received in revised form 2 April 2025; Accepted 3 April 2025
Available online 8 April 2025

(Alley et al., 2021; Calvin et al., 2023). Anthropogenic greenhouse gas emissions are the primary drivers of these changes, leading to rising global surface temperatures that influence both the intensity and variability of hydrological processes (Pachauri et al., 2014; Shindell et al., 2013). According to the IPCC's 2023 report, global surface temperatures have increased more rapidly since 1970 than during any other 50-year period in the past two millennia. This temperature rise, combined with more frequent and intense precipitation events, has become increasingly pronounced since the 1950s, largely attributable to human-induced climate change (Calvin et al., 2023). These changes have led to more frequent occurrences of agricultural and ecological droughts in certain regions, driven by heightened evapotranspiration rates (Cook et al., 2015; Trenberth et al., 2013).

Developing countries, particularly those with limited adaptive capacities, are especially vulnerable to these shifts, complicating water resource management under changing climate conditions (Kusangaya et al., 2014). In North Africa, for example, the Atlas Mountains is a critical "water tower," supplying water for agriculture, urban water needs, and industrial activities downstream. However, the stability of these water resources is increasingly threatened by climate change, which disrupts seasonal snowmelt and precipitation patterns that sustain regional water supplies (Schilling et al., 2012; Tramblay et al., 2013). Global studies in mountainous regions such as the European Alps, the Himalayas, and the Andes have demonstrated consistent climate-driven hydrological shifts, including reduced snowpack and glaciers, earlier snowmelt, and altered river flow patterns (Barnett et al., 2005; Gobiet et al., 2014; Huss and Hock, 2018; Immerzeel et al., 2010), Research focusing on the Atlas Mountains water resources in Morocco remains limited on single basins. Projections using models from the Med-CORDEX and Euro-CORDEX initiatives indicate significant reductions in water availability under high-emission scenarios, primarily due to decreased precipitation and increased evapotranspiration (El Khalki et al., 2021; Filahi et al., 2017; Marchane et al., 2017; Tramblay et al., 2020; Tramblay and Somot, 2018). For instance, snow cover in this region could decline by up to 50 % by the end of the century, severely affecting river flows during critical spring and summer (Hanich et al., 2022; Tuel et al., 2022). Yet, there is no regional assessment of these changes in different basins.

Understanding how climate change impacts hydrological processes in the Atlas Mountains is essential for effective water resource management. While existing research provides insights into large-scale climatic changes, studies focused on the interconnected basins of the Atlas region remain sparse. This study aims to bridge this gap by assessing climate change impacts on water availability across multiple mountainous basins in Morocco. Precipitation, evapotranspiration, and river discharge across multiple basins are simulated by a CORDEX-Africa multi-model ensemble (CMIP5) under the RCP 8.5 scenario. This research is novel in its multi-basin and multi-model approach in North Africa using observed data and two hydrological models to assess the impacts of climate change on river flow. The HYPE (Hydrological Predictions for the Environment) model and the GR4J-CemaNeige model, able to reproduce snowmelt effects on river discharge, are utilized to provide future hydrological scenarios. By examining the influence of basin characteristics on model

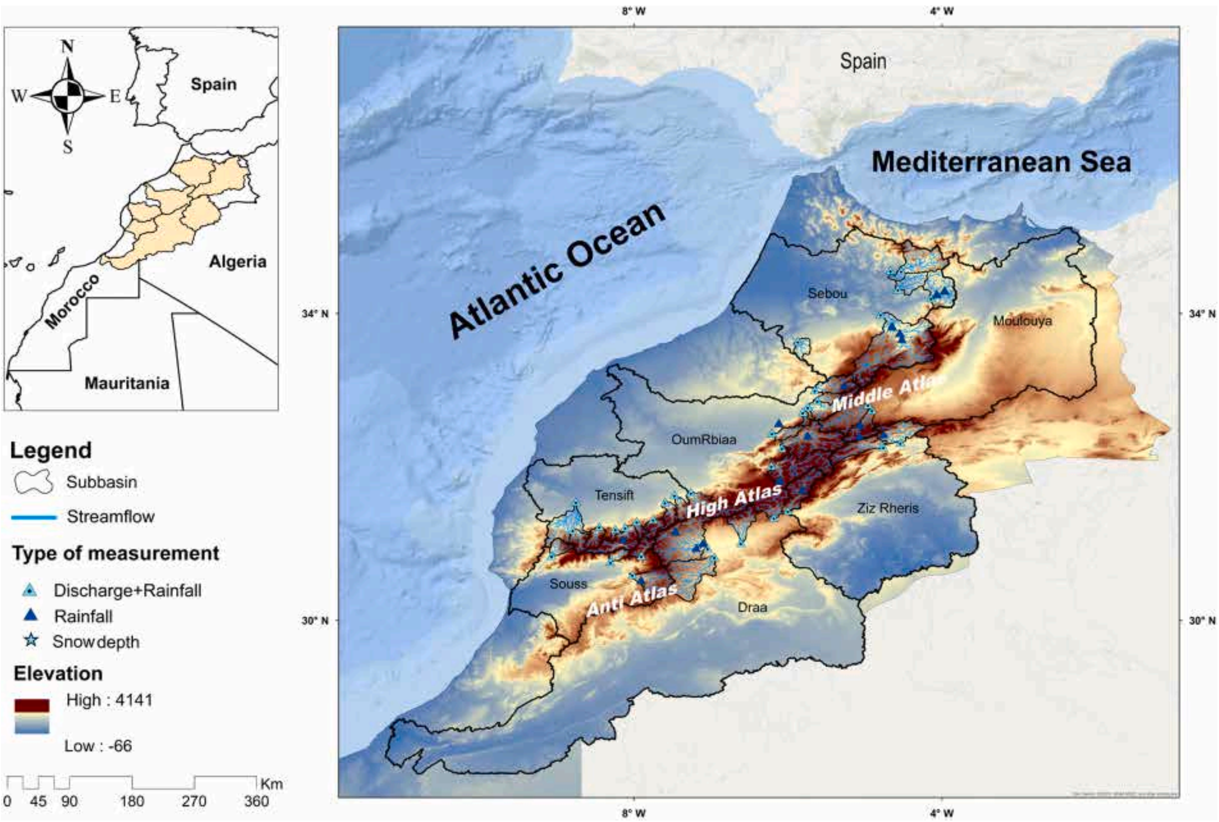

Fig. 1. Location of sub-basins with elevation and distribution of measurement stations in the study region.

performance as well as the variability in climate change projections, this study offers a deeper understanding of how these factors shape future water availability. The findings of this research are expected to provide valuable insights at the scale of Morocco for adaptive water management strategies and support the sustainable use of water resources in the face of a changing climate.

2. Data and methods

2.1. Study area

The Atlas Mountains constitute a prominent geographical feature of North Africa, extending across Morocco, Algeria, and Tunisia, and play a crucial role in shaping the region's hydrological systems. In Morocco, the Atlas range is traditionally divided into three major sections: the Middle Atlas, the High Atlas, and the Anti-Atlas. Among these, the High Atlas is particularly noteworthy for its capacity to retain and distribute water, as it encompasses Mount Toubkal, North Africa's highest peak at 4167 m. This mountainous terrain acts as a natural climatic barrier, preventing moist Mediterranean and Atlantic air masses from reaching the arid desert regions to the south.

This study focuses on 36 river basins distributed across the Moroccan Atlas Mountains (Fig. 1). These basins were selected for their diverse climatic and hydrological characteristics, to evaluate the impacts of climate change on water availability under high-emission scenarios. They are mainly fed by snowmelt and seasonal rainfall, which are crucial for maintaining river flow and groundwater recharge. Their water resources support key socio-economic activities, such as agriculture, hydropower, and domestic water supply, and therefore vital for the livelihoods of local populations.

The climate in the Atlas Mountains varies significantly with altitude and orientation. The northern slopes, exposed to Mediterranean influences, experience cool, wet winters and hot, dry summers, while the southern slopes, facing the Sahara, are markedly drier (Chaponnière, 2005). Annual precipitation ranges from approximately 600 mm in the Middle Atlas and northern High Atlas to less than 200 mm in the southern Anti-Atlas (Hanich et al., 2022). Snowfall in the High Atlas plays a critical role in the region's hydrological cycle, as snowmelt during the spring and summer months sustains river flows essential for downstream agricultural and urban areas (Boudhar, 2009; Boudhar et al., 2009; Hanich et al., 2022; Marchane et al., 2014).

Given the significant variability in climatic conditions and water availability across these basins, the Atlas Mountains present a unique and valuable case study for assessing the impacts of climate change on water resources. By focusing on multiple interconnected basins, this study aims to explore how variations in basin characteristics such as altitude, slope, and land cover affect the performance of hydrological models and shape climate change projections. Understanding these dynamics is essential for developing adaptive water management strategies, particularly in a region where water resources are becoming increasingly vulnerable to climate-induced changes (Beniston et al., 2011; García-Ruiz et al., 2011).

Moreover, the selected basins reflect broader hydrological challenges typical of semi-arid regions globally such as high climate variability, water scarcity, and vulnerability to drought (Kreamer, 2012; Vörösmarty et al., 2000). By investigating how changes in temperature and precipitation under the high-emission RCP 8.5 scenario affect river discharge and water availability, this research provides critical insights into the future sustainability of water resources. These findings will not only inform water management policies in Morocco but also offer valuable lessons for other regions facing similar challenges (Schilling et al., 2020).

2.2. In-situ precipitation and discharge data

For this study, we retrieved data from 53 rain gauges and 36 discharge stations across various Moroccan river basins from 1989 to 2014. This period was selected based on data availability to ensure a continuous dataset. The rain gauges are located in the Tensift Basin (10 stations), the Oumrbiaa Basin (9 stations), the Souss Massa Basin (5 stations), the Draa Oued Noun Basin (11 stations), the Sebou Basin (11 stations), the Moulouya Basin (4 stations), and the Ziz Rheris Basin (3 stations). These datasets provide daily precipitation records. The studied catchments vary widely in size, with upstream areas ranging from 100 km^2 to 3000 km^2, ensuring that both small and large basins are represented in the analysis.

A rigorous quality control process is implemented and applied to ensure the data's reliability and consistency. Out of the 53 available precipitation stations, only 36 are retained for use in the study, given the numerous gaps found in many stations. These retained stations are located at the outlets of catchments and are selected based on their data completeness and quality. These stations also most often located close to the hydrometric stations that provides daily discharge records, critical for validating the hydrological models. However, the rain gauges used in the study do not include direct measurements of snowfall.

Snow significantly contributes to streamflow generation in high-altitude regions of our study area. Due to the limited observational network, snow depth measurements from the Oukaimeden station (3250 m) available daily since 2011 are utilized to derive snow water equivalent (SWE), following the empirical relationship established by Boudhar et al. (2009). These SWE estimates are then used together with rainfall in the hydrological models for the different basins to represent snowpack dynamics more realistically. Although spatially limited, this approach provides a better calibration of snow-related processes in both HYPE and GR4J-CemaNeige models. Preliminary tests showed that it was not possible to obtain satisfactory calibration results using rain data alone, which is quite expected in mountainous basins. A detailed analysis of the modelled contribution of snowmelt to runoff is presented in the Results section. The spatial distribution of the 36 retained meteorological stations and the Oukaimeden snow station is presented in Fig. 1, with their geographic coordinates detailed in **Table A.1** in the supplementary materials. While the retained stations provide essential data for the study, the network remains sparse, limiting spatial coverage and potentially underrepresenting precipitation variability, especially in areas with complex topography. Nonetheless, the selected stations serve as a key dataset for capturing the hydrological variability of the studied basins.

2.3. Climate data

Gridded climate datasets are essential for providing high-resolution, long-term data on precipitation and temperature with complete spatiotemporal coverage, particularly in data-scarce regions. This study employs two widely used datasets: ERA5 reanalysis data for temperature (at ~0.25° spatial resolution) and CHIRPS v2.0 for precipitation (at ~0.05° resolution). These datasets have demonstrated satisfactory performance in North Africa, including mountainous and semi-arid regions (Ahmed et al., 2024). However, several studies have reported potential biases in both datasets that must be considered. For example, ERA5 may underestimate temperature variability in complex topographies, while CHIRPS can underrepresent extreme rainfall events, especially in arid environments (Gebrechorkos et al., 2024; Lavers et al., 2022b). In our study, CHIRPS precipitation and ERA5 temperature were used to calibrate and validate the hydrological models. The use of spatially continuous and bias-assessed reanalysis products ensured input consistency across the domain and supported robust model performance evaluation. While reanalysis products provide consistent and gap-free coverage, they have limitations, and their uncertainties can propagate through the modelling chain. Therefore, acknowledging both the strengths (e.g., spatial completeness, consistency) and limitations (e.g., systematic errors, local-scale inaccuracies) of reanalysis data is important in the context of hydrological modelling under climate change scenarios.

2.4. ERA5

ERA5 is the fifth-generation reanalysis dataset developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). This dataset provides atmospheric, oceanic, and land data with a spatial resolution of 25 km and hourly temporal coverage (Hersbach et al., 2020). ERA5 integrates diverse observational inputs, including surface-based measurements and satellite-derived data, to produce consistent estimates of atmospheric variables.

In this study, 2-meter air temperature data from ERA5 are used as inputs for hydrological modelling. The dataset's reliability in representing temperature trends has been validated in various climatic contexts, particularly for long-term analyses (Beck et al., 2021). Additionally, ERA5 data are employed to correct biases in climate model simulations, ensuring an accurate representation of local temperature variations. This correction step is especially critical in regions with complex topographies, where raw climate model outputs can exhibit significant discrepancies (Jiao et al., 2021; Lavers et al., 2022).

2.5. CHIRPS v2.0

The Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset provides high-resolution precipitation data (~5 km spatial resolution) with daily, monthly, and annual temporal coverage. CHIRPS integrates satellite infrared data with in-situ precipitation observations, offering long-term coverage starting in 1981 (Funk et al., 2015). Its design enables effective monitoring of rainfall variability and drought conditions, particularly in semi-arid and mountainous regions.

For this study, CHIRPS data are employed as precipitation-forcing data to refine hydrological model calibration by improving the representation of rainfall-runoff processes. Additionally, CHIRPS data are utilized to correct biases in precipitation simulations from climate models, ensuring consistency with observed precipitation patterns. The dataset's demonstrated accuracy in capturing rainfall dynamics in complex terrains was particularly advantageous for this study's focus on semi-arid basins (Dembele et al., 2020; Katsanos et al., 2016).

Both ERA5 and CHIRPS datasets have distinct yet complementary roles within our methodological framework. ERA5 is specifically employed to provide temperature data (~0.25° spatial resolution), crucial for accurately representing temperature variability across the study domain. In contrast, CHIRPS is used for precipitation due to its finer spatial resolution (~0.05°) and detailed temporal coverage, which is particularly beneficial in capturing precipitation variability. Importantly, these datasets are integral to our bias-correction strategy. We apply ERA5 (temperature) and CHIRPS (precipitation) data to correct biases inherent in the outputs of regional climate models (RCMs). This step enhances the reliability and representativeness of climate inputs subsequently fed into our hydrological models. Employing these corrected datasets for hydrological model calibration, in place of scarce observations, ensures consistency across basins, this is particularly important given the region's complex terrain and climatic variability (Beck et al., 2021; Dembele et al., 2020). Additionally, discharge measurements from gauging stations located within the Atlas Mountain basins serve as primary observational benchmarks for validating hydrological simulations. Although in-situ precipitation data are available and presented on the map, preliminary calibration trials indicated inadequate results due to their sparse spatial distribution and limited basin-scale representativeness. Thus, CHIRPS precipitation was ultimately selected for calibration and validation, ensuring methodological consistency with the bias correction of climate model outputs based on the same reanalysis datasets.

2.6. Climate models

In this study, future climate variables are obtained using CORDEX Africa data to assess the impact of climate change on water resources in the Atlas Mountains. The Coordinated Regional Climate Downscaling Experiment (CORDEX) provides high-resolution projections by downscaling global climate models (GCMs) to better capture regional climate patterns (Giorgi et al., 2009). In this study, the CORDEX data have a spatial resolution of 25 km, achieved through bias correction using reference datasets such as ERA5 for temperature and CHIRPS for precipitation. This high resolution is crucial for accurately representing the complex topography and climatic variability of the Atlas Mountains. Nevertheless, we acknowledge that the CORDEX ensemble, comprising only 9 simulations, may not fully encompass the structural uncertainties inherent to climate models. This ensemble size represents a necessary compromise: while a larger ensemble could offer a more comprehensive uncertainty assessment, the limited availability of high-resolution climate simulations in the CORDEX Africa experiment restricts our options (Dosio et al., 2015, 2019; Nikulin et al., 2012).To link the gridded data to specific basins, the grid cells intersecting the study basins are identified using a shapefile of the basin boundaries. Climate variables from the selected grid cells are then averaged at the basin scale to represent the spatially aggregated climate conditions for each basin. This approach ensures that the unique characteristics of each basin are reflected in the analysis while maintaining the spatial resolution of the climate data.

This study focuses on the RCP 8.5 scenario, a high-emission pathway that projects significant increases in greenhouse gases throughout the 21st century. This scenario is widely used to assess severe climate impacts, especially in vulnerable regions like North Africa, where rising temperatures and changes in precipitation patterns are expected to be particularly pronounced (Calvin et al., 2023; Stocker, 2013). The selection of RCP 8.5 is dictated by data availability, as the projections used in this study are only available under this scenario. The analysis includes two future periods (2040–2060 and 2070–2100) compared to a historical baseline (1975–2005).

A bias correction is applied using the Cumulative Distribution Function transform (CDFt) method (Michelangeli et al., 2009), calibrated against ERA5 for temperature and CHIRPS for precipitation. The CDFt method, a variant of quantile mapping adapted to non-stationary conditions, has been widely applied in previous studies in many different regions(Ayar et al., 2021; Famien et al., 2018; Luo et al., 2025; Michelangeli et al., 2009; Vrac et al., 2016; Zhu et al., 2022a, 2022b).In our implementation, transfer functions are computed on a daily basis to capture daily variability accurately. For precipitation, a pre-processing step is performed to reduce the drizzle effect by applying a minimum threshold. This approach enhances the consistency between model outputs and observed distributions, thereby improving the reliability of hydrological projections. The methodology is implemented using the SBCK (Statistical Bias Correction Kit) Python package, which provides a robust and flexible framework for multivariate bias correction of climate simulations (Robin and Vrac, 2021). The code and detailed documentation are publicly available at https://github.com/yrobink/SBCK-python.

Recognizing the uncertainties inherent in climate modelling, this study employs nine RCMs simulations from the CORDEX ensemble (Table 1) to capture a range of possible climate futures (Giorgi et al., 2009). Global climate models (GCMs) often show significant divergences in their projections, particularly in representing regional processes critical for hydrology, such as precipitation variability and orographic effects (Christensen and Lettenmaier, 2007). Using a multi-model approach, incorporating an ensemble of climate models, helps address these uncertainties in projections for the Atlas Mountains (Muerth et al., 2013).

2.7. Hydrological modeling approach

For the purpose of this study, two hydrological models were selected: the HYPE (Hydrological Predictions for the Environment) model and the GR4J-CemaNeige model. This selection was driven by the necessity to capture diverse hydrological processes and evaluate uncertainties inherent in simulating complex water systems under climate change conditions. It is important to emphasize that the choice of hydrological models can significantly influence hydrological projections and, consequently, climate impact assessments (Clark et al., 2016; Vetter et al., 2017). In addition to data availability and computational constraints, our selection of two hydrological models with different structural approaches was primarily guided by the study's specific objectives. Using multiple models aligns with current practices in hydrological sciences, enabling a comprehensive assessment of uncertainty and enhancing the reliability of hydrological predictions under climate change scenarios (Fatichi et al., 2016; O'Connell and Todini, 1996)

2.7.1. HYPE model

The HYPE model, a semi-distributed model, has been widely used and validated in diverse climates and regions, including Sweden (Pechlivanidis et al., 2014; Strömqvist et al., 2012), the Baltic Sea basin(Arheimer et al., 2012), Europe (Donnelly et al., 2016), the Indian subcontinent (Pechlivanidis and Arheimer, 2015), and the Niger River (Andersson et al., 2017) and on global scale (Arheimer et al., 2020). One of the main advantages of HYPE is its open-source code, which allows for flexible adaptation and parameterization. This model is especially suitable for climate change impact assessments, where it has demonstrated robust performance compared to other models across various global sites (Donnelly et al., 2016; Gelfan et al., 2017; Gosling et al., 2017).

For this study, the HYPE model setup is derived from the World-Wide HYPE framework, which provides a global hydrological

Table 1
Forcing GCMs and RCMs used in this Study.

Driving GCM	RCM	Resolution	Abbreviation
CCCma-CanESM2	RCA4 v1	0.25°	CCCma
CNRM-CERFACS-CNRM-CM5	RCA4 v1	0.25°	CNRM
ICHEC-EC-EARTH	RCA4 v1	0.25°	ICHEC
NOAA-GFDL-GFDL-ESM2M	RCA4 v1	0.25°	NOAA
MPI-M-MPI-ESM-LR	RCA4 v1	0.25°	MPI
NCC-NorESM1-M	RCA4 v1	0.25°	NCC
MIROC-MIROC5	RCA4 v1	0.25°	MIROC
CSIRO-QCCCE-CSIRO-Mk3–6–0	RCA4 v1	0.25°	CSIRO
IPSL-IPSL-CM5A-MR	RCA4 v1	0.25°	IPSL

model adapted to regional and basin-level applications (Arheimer et al., 2020). The World-Wide HYPE provides a global setup, offering predefined parameters and catchment geographical delineations. This setup is further refined to align with the specific characteristics of the study area, incorporating local data were available to enhance accuracy. The adaptation includes calibrating parameters relevant to snowmelt dynamics, surface-groundwater interactions, and precipitation-runoff processes, ensuring that the model accurately represents the hydrological dynamics of mountainous regions like the Atlas Mountains.

HYPE's ability to model complex hydrological processes and its flexibility in parameterization make it particularly well-suited for mountainous regions. Additionally, the extensive validation and active scientific support, along with detailed documentation, make HYPE a suitable choice for assessing the impacts of climate change on water resources in multi-basin systems.

2.7.2. GR4J-CemaNeige model

Conceptual hydrological models, such as the GR models, are widely used in studies assessing the impacts of climate change on water resources (Mouelhi et al., 2006, 2004; Perrin, 2002; Perrin et al., 2003). However, the inherent simplifications in conceptual models can limit their ability to fully capture complex hydrological processes under changing climatic conditions, particularly when it comes to simulating drought events. For example, the aggregated representation of catchment processes may not accurately reproduce detailed soil moisture dynamics, evapotranspiration feedback, and groundwater contributions that are crucial for simulating drought. Furthermore, calibration based on historical discharge may not encompass the full range of future variability induced by climate change since this type of model does not explicitly reproduce energy and water budgets. While these models remain valuable tools for assessing water balance and snow-driven processes in data scarce regions, their application for drought analysis should be interpreted with caution. Future studies could enhance drought simulation by using more physically based approaches or by refining the model parameterizations to better represent drought-related processes.

The GR4J-CemaNeige model is chosen for its simplicity and effectiveness in simulating hydrological balance, combined with CemaNeige's capacity to simulate snow dynamics. This is particularly crucial in regions where snow provides a significant water source. The integration of snow processes with other components of the water cycle, such as precipitation and runoff, enhances its applicability in mountainous environments. A schematic overview of the hydrological processes and key governing equations represented in the GR4J-CemaNeige model, along with those of the HYPE model used in this study, is provided in the supplementary material (**Figure A.1**) to offer a clearer understanding of their conceptual structures.

The GR4J-CemaNeige model has been applied in various studies within Morocco to assess the impacts of climate scenarios on water resources (Boumenni et al., 2017; Hajhouji et al., 2020, 2018). Its implementation is further facilitated by the availability of application tools such as the airGR package in R (Coron et al., 2017), which simplifies model calibration and analysis.

2.7.3. Model calibration and validation

The calibration and validation of the HYPE and GR4J-CemaNeige hydrological models relied on observed discharge data from gauging stations across various basins in the Atlas Mountains. These data served as the main benchmark for evaluating model performance. However, observational data for precipitation proved significantly limited. Available precipitation data contained substantial gaps and were unevenly distributed, compromising their spatial representativeness. Additionally, no observed temperature data were available for the region.

To address these limitations, we utilized CHIRPS precipitation and ERA5 temperature datasets, which offer spatially continuous and temporally consistent gridded data. This approach ensured coherent climate forcing across all basins, a key requirement for reliable hydrological simulations. It is important to note that while model calibration was performed with observed discharge data, CHIRPS and ERA5 datasets were used as climate data inputs due to the lack of reliable and spatially complete observational data.

The calibration process covered the period from 1989 to 2000, during which model parameters were adjusted to maximize agreement between simulated and observed discharge. In the HYPE model, this process refined parameters related to snowmelt, soil moisture, and surface runoff. The GR4J-CemaNeige model focused on snow accumulation and runoff generation, consistent with its emphasis on snow-driven hydrological processes. Incorporating CHIRPS precipitation data enhanced the spatial representation of rainfall variability, particularly in regions with sparse gauge networks (Dinku et al., 2018; Gebrechorkos et al., 2024). Regarding temperature, we did not have observed data available and thus relied on ERA5 temperature data, acknowledging potential biases associated with this dataset, especially in mountainous areas characterized by steep temperature gradients.

The calibration of the HYPE model involved fine-tuning 15 key parameters that govern various hydrological processes. Each parameter was constrained within physically plausible bounds based on hydrological theory and previous applications (Arheimer et al., 2020):

- Snowmelt rate (mm/day): Calibrated within a range of 2–5; controls the rate at which snow is converted to runoff.
- Evapotranspiration correction factor (–): Calibrated between 0.1 and 0.3; modulates the partitioning of precipitation between evapotranspiration and runoff.
- Percolation rate (mm/day): Explored within 5–100; governs vertical water movement through soil layers.
- Soil moisture storage (–): Calibrated between 0.05 and 0.5; defines the water-holding capacity of soil layers.
- Effective porosity (–): Set within 0.05–0.5; affects the proportion of soil volume available for water transport.
- Runoff coefficient (–): Varied between 0.05 and 0.5; dictates the fraction of precipitation contributing directly to surface runoff.
- River flow velocity (m/s): Calibrated between 0.5 and 2; determines the speed of water movement within the river network.
- Lake depth (m): Adjusted within 5–10; represents the vertical storage capacity of lakes.

- Rating curve parameters (–): Two coefficients, calibrated between 1–100 and 1–2, respectively, that control the relationship between water storage and observed discharge.

An iterative calibration procedure was applied, guided by a global sensitivity analysis to prioritize influential parameters. Initial calibration was conducted on representative basins grouped according to soil and land use characteristics. Optimization was performed using the Kling-Gupta Efficiency (KGE) metric, which combines correlation, bias, and variability ratios.

For the GR4J-CemaNeige model, calibration focused on six core parameters:

- X1 (mm): Maximum capacity of the production reservoir; calibrated between 100 and 1200.
- X2 (mm): Exchange coefficient between production and routing reservoirs; calibrated between –5 and 3.
- X3 (mm): Capacity of the routing reservoir; calibrated between 20 and 300.
- X4 (days): Time constant of the routing reservoir; calibrated between 1 and 5.
- CNX1 (°C): Threshold temperature for snow accumulation; calibrated between –2 and 2.
- CNX2 (mm/day): Degree-day melt factor; calibrated between 0.1 and 0.3.

The GR4J-CemaNeige calibration employed the "Calibration_Michel" algorithm from the airGR package (Coron et al., 2017). This method used a grid-search approach to determine optimal parameter values based on the KGE metric. The KGE provides a comprehensive assessment of hydrological performance by combining correlation, bias ratio, and variability ratio (Gupta et al., 2009).

To ensure model robustness, a split-sample approach divided the data into calibration (1989–2000) and validation (2001–2014) periods (Liu et al., 2018). This approach tested the models' ability to generalize beyond the calibration period, minimizing the risk of overfitting. Subsequently, the hydrological models were forced with bias-corrected climate simulations using CHIRPS and ERA5 datasets. This correction step ensured that climatic inputs were representative of the study area's conditions, providing a solid foundation for future hydrological projections under changing climate scenarios.

2.8. Analysis of hydrological droughts

A systematic approach is employed to identify and compare hydrological drought characteristics across historical and future periods (Hodgkins et al., 2024). Simulated daily discharge data, from the HYPE and GR4J-CemaNeige models, driven by CORDEX climate data, are processed using a 7-day moving average (MA7) to smooth short-term fluctuations and detect low-flow conditions (Smakhtin, 2001; Tallaksen and Lanen, 2004). The low-flow threshold is calculated as the 10th percentile of the smoothed discharge (MA7) during the historical period, representing baseline conditions for each basin (Hisdal et al., 2000; Smakhtin, 2001). Drought episodes are identified as consecutive days when the MA7 discharge values remained below this threshold, and each episode is characterized by its start and end dates, duration, and maximum intensity. To ensure consistency, the same threshold and methodology are applied to climate projections under the RCP8.5 scenario for the periods 2040–2060 and 2070–2100. Additionally, the seasonal occurrence of droughts is examined by mapping the start and end dates of episodes to their respective months, allowing the identification of potential shifts in the timing of hydrological stress periods under future climatic conditions.

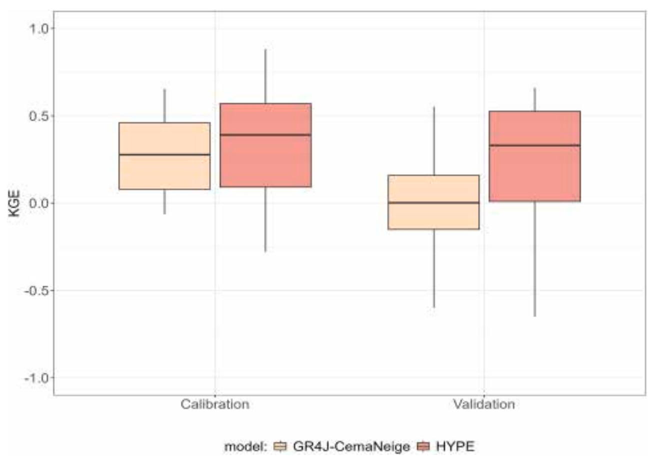

Fig. 2. Boxplot of KGE Scores for Calibration and Validation of HYPE and GR4J-CemaNeige Models.

3. Results and discussion

3.1. Model performance

3.1.1. Overall performance

The performance of the GR4J-CemaNeige and HYPE hydrological models was assessed using the Kling-Gupta Efficiency (KGE) criterion for daily discharge over both calibration and validation periods (Fig. 2). Across all studied basins, median daily KGE values obtained during calibration were 0.44 for HYPE and 0.38 for GR4J-CemaNeige. Representative hydrographs comparing observed and simulated discharge (Fig. 3) illustrate that both models effectively capture the overall discharge dynamics, particularly during events driven by snowmelt processes.

However, clear discrepancies remain evident, particularly regarding accurately simulating peak discharge magnitudes. These discrepancies are most pronounced during high-flow conditions and may result from inadequate representations of critical processes and complex spatial variability in mountainous regions, factors previously highlighted by studies (Gascoin, 2021; Hanich et al., 2024). Additionally, the lack of spatially distributed snow measurements could significantly alter observed snowmelt dynamics and, consequently, the hydrological response, further contributing to observed deviations.

Moreover, the analysis of the annual discharge cycle (**Figure A.2** in the supplementary materials) highlights both models' capabilities in simulating seasonal discharge variability, effectively simulating river flows typically occurring in winter and early spring due to snowmelt. Although these seasonal patterns are generally captured, observed differences between simulated and actual peak discharges emphasize the ongoing need for improved model representations of snow dynamics and associated hydrological processes.

Further detailed analyses of these hydrological processes, including the quantification of snowmelt's contribution to total discharge, are presented in subsequent sections of the manuscript.

3.1.2. Spatial variability

The spatial variability of model performance is evident in the distribution of Kling-Gupta Efficiency (KGE) values across the study area (Fig. 4). Both models generally achieve higher KGE values during the calibration phase. The HYPE model consistently outperforms GR4J-CemaNeige across most regions, achieving higher KGE values in both calibration and validation phases, which indicates its robustness in simulating hydrological processes under varying climatic and physiographic conditions.

In contrast, GR4J-CemaNeige shows weaker performance during validation, particularly in the southwestern regions, where KGE values are notably lower. This discrepancy primarily occurs during high-flow events, indicating limitations in the model's ability to accurately represent rapid runoff generation, infiltration excess, and surface-subsurface flow interactions. These limitations suggest challenges in generalizing model performance beyond calibration conditions and highlight the importance of better addressing spatial variability to improve model reliability in diverse hydrological settings.

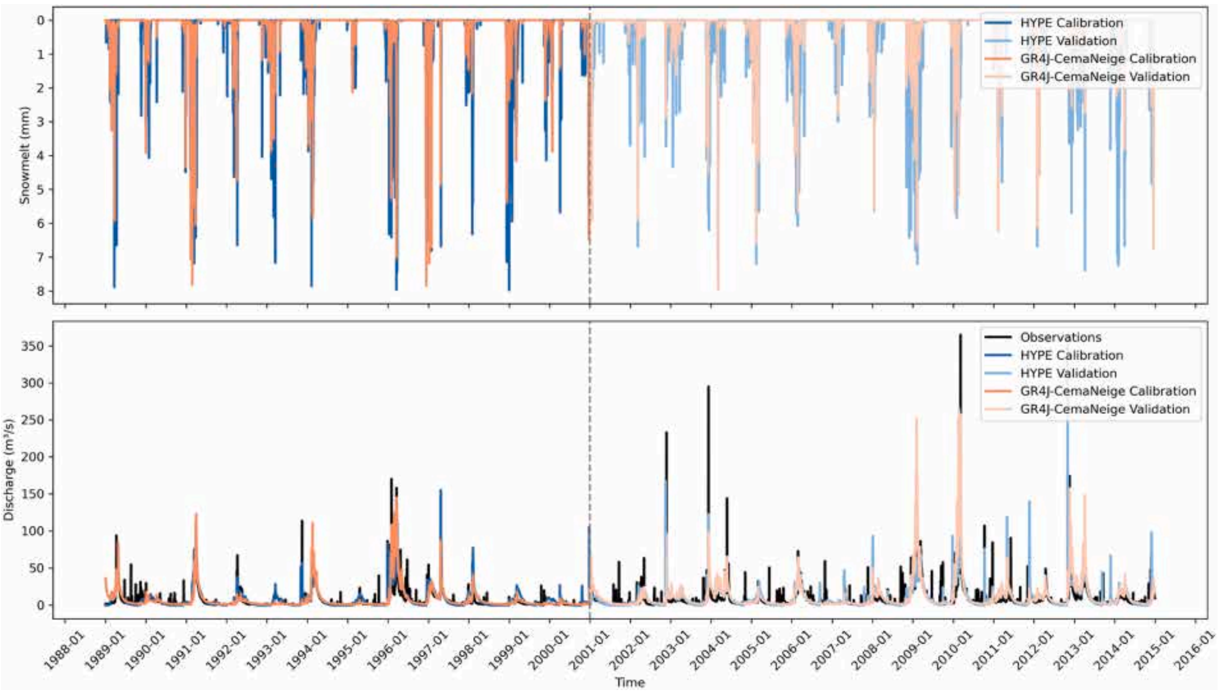

Fig. 3. Representative hydrographs showing observed and simulated daily discharge and snowmelt for a representative basin (Ait Ouchene basin) during calibration and validation periods.

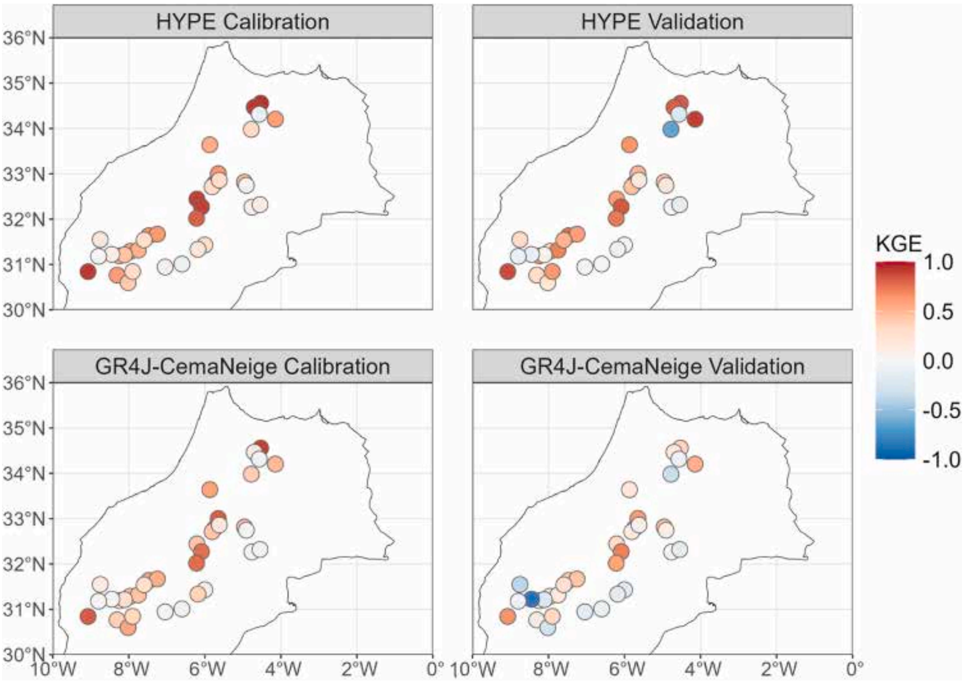

Fig. 4. Spatial Distribution of KGE for HYPE and GR4J-CemaNeige Models.

3.1.3. Influence of basin characteristics

The correlation analysis between model performance and basin characteristics is presented in Fig. 5. To assess these relationships, key basin attributes such as slope, land use, soil type, and the aridity index are analyzed. The aridity index is calculated using De Martonne's formula (Martonne, 1926), which is based on precipitation and temperature data, while other basin characteristics are sourced from publicly available databases, as detailed in the supplementary materials (**Table A.2**).

The results reveal that certain basin characteristics are positively correlated with model performance, as measured by the Kling-Gupta Efficiency (KGE). Specifically, higher annual mean precipitation, greater forest cover, and a larger proportion of irrigated cropland are linked to improved model accuracy. This suggests that hydrological models generally perform better in regions with greater water availability and stable land cover conditions. Conversely, negative correlations, especially with the aridity index, indicate a decline in model accuracy in drier areas.

In addition, basin size does not emerge as another important factor to explain model performance. Smaller basins typically respond more quickly to precipitation events due to lower storage capacity and shorter concentration times, leading to more pronounced short-term variability in discharge. Larger basins, by contrast, tend to exhibit a more buffered or delayed response because of their greater storage capacity. This distinction in hydrological response behavior can partly explain the variability in model performance across basins of different sizes. The results presented herein indicate the climatic conditions may be a more important factor to explain the hydrological model performance across the basins, since also the basin sample does not include basins larger than 3000 km^2.

The findings further indicate that the HYPE model outperforms GR4J-CemaNeige in simulating discharge in the Atlas Mountains during both the calibration and validation phases. This superior performance can be attributed to HYPE's capability to represent complex hydrological processes, such as snowmelt dynamics and surface-groundwater interactions, which are particularly important in mountainous regions. However, GR4J-CemaNeige might provide complementary insights, potentially performing better at

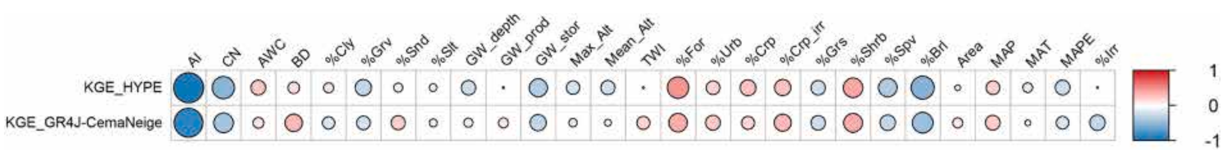

Fig. 5. Correlation Matrix of KGE Scores from HYPE and GR4J-CemaNeige Models and Basin Characteristics., **Notes:** AI: Aridity Index, CN: Curve Number, AWC: Available Water Capacity, BD: Bulk Density, %Cly: %Clay, %Grv: %Gravel, %Snd: %Sand, %Slt: %Silt, GW_depth: Groundwater Depth, GW_prod: Groundwater Productivity, GW_stor: Groundwater Storage, Max_Alt: Maximum Altitude, Mean_Alt: Mean Altitude, TWI: Topographic Wetness Index, %For: %Forest, %Urb: %Urban, %Crp: %Cropland, %Crp_irr: %Cropland Irrigated, %Grs: %Grassland, %Shrb: %Shrubland, %Spv: %Sparse Vegetation, %Brl: %Bare Land, Area: Basin Area, MAP: Mean Annual Precipitation, MAT: Mean Annual Temperature, MAPE: Mean Annual Potential Evapotranspiration, %Irr: %Irrigation, KGE_HYPE: Kling-Gupta Efficiency of HYPE model, KGE_GR4J-CemaNeige: Kling-Gupta Efficiency of GR4J-CemaNeige model.

representing specific processes or adapting to temporal changes not evaluated numerically in this study. The spatial variability in model performance underscores the critical role of local factors such as topography, land use, and climatic conditions. Incorporating basin-specific characteristics into model calibration could further enhance predictive accuracy. These findings underscore the value of multi-model approaches in climate change impact assessments, as each model brings distinct structures, parameterizations, and assumptions (Giuntoli et al., 2015). By encompassing a broader range of uncertainties and perspectives, multi-model ensembles lead to more robust and reliable projections under evolving climate conditions. Furthermore, choosing models suited to the basin's characteristics and research objectives remains critical for ensuring accuracy and relevance in hydrological studies.

3.2. Climate change projections

3.2.1. Projected changes in precipitation

To assess future precipitation changes, we first examine the annual precipitation cycle to evaluate seasonal variability and compare historical simulations with observations. **Figure A.3** in the supplementary materials presents a comparison of observed and modeled historical precipitation cycles (1975–2005), highlighting a tendency of climate models to overestimate precipitation during the wet season, particularly in February and March, while performing well during drier months.

Under the RCP8.5 scenario, precipitation is projected to decrease, particularly in the wet season. As shown in **Figure A.4** (supplementary materials), moderate reductions are expected during 2040–2060, with significant declines in February, March, and December. By 2070–2100, this drying trend intensifies, especially in winter and early spring. However, precipitation levels during the driest months (July and August) remain relatively stable across all periods, leading to an increasing seasonal contrast.

3.2.2. Spatial distribution of precipitation changes

Precipitation changes across Morocco exhibit significant regional variations under the RCP8.5 high-emission scenario. Fig. 6 presents the spatial distribution of mean relative precipitation changes (%) for 2040–2060 and 2070–2100.For 2040–2060, moderate declines of −11 % to −23 % are projected, particularly in the southern Atlas region, potentially exacerbating existing water scarcity issues. By 2070–2100, reductions intensify, reaching up to −43 % in some areas, especially in the southwest, indicating a progressive drying trend over time.

While some regions experience significant decreases, others may remain relatively stable or even see slight increases, highlighting spatial variability in climate change impacts. These projected shifts in precipitation patterns have major implications for water resources, agriculture, and ecosystem stability, emphasizing the need for region-specific adaptation strategies.

3.2.3. Inter-Model Variability in Precipitation Projections

The magnitude of precipitation changes varies across climate models. **Figure A.5** (supplementary materials) shows the mean relative change in precipitation (%) projected by different models for 2040–2060 and 2070–2100. While all models indicate declining precipitation, the extent of reduction differs: MIROC-MIROC5 and NOAA-GFDL-GFDL-ESM2M project the steepest declines, exceeding 30 % by 2070–2100, while CCCma-CanESM2 and ICHEC-EC-EARTH suggest reductions below 20 %.

This variability is further illustrated in **Figure A.6** (supplementary materials), which presents a boxplot of precipitation changes across basins for different models. For 2040–2060, median reductions range between −10 % and −30 %, with some models exhibiting significant outliers. By 2070–2100, the spread widens, reflecting increased uncertainty in long-term projections.

3.2.4. Projected changes in potential evapotranspiration

To assess future changes in potential evapotranspiration (PET), we first examine the historical annual cycle to compare observed and simulated PET values. **Figure A.7** (supplementary materials) presents the mean daily cycle of potential evapotranspiration (PET) for the period 1975–2005, highlighting a pronounced seasonal pattern with a peak occurring in July, coinciding with the warmest

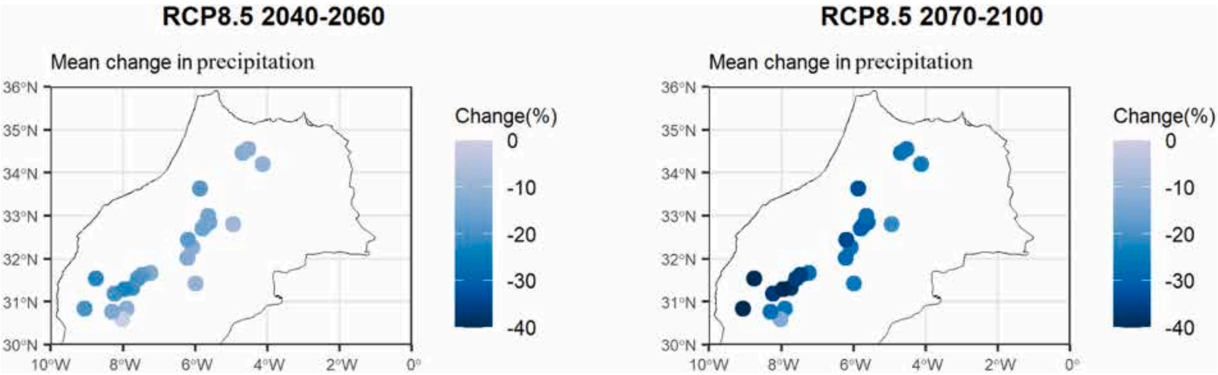

Fig. 6. Spatial Distribution of Mean Relative Change in Precipitation (%) relative to the historical period (1975–2005) for 2040–2060 and 2070–2100.

months and highest solar radiation. The PET values used here are calculated using the temperature-based formulation developed by Oudin et al. (2005), based on ERA5 air temperature, and are used as reference data in the absence of direct temperature observations to compute PET. These PET estimates consistently exceed those simulated by historical climate models, especially during peak months. This discrepancy may result from biases inherent in the reanalysis inputs or from limitations in the climate models' representation of atmospheric processes affecting evapotranspiration, such as radiation, humidity, and wind speed (Mcfarlane, 2011; Trenberth et al., 2007). Future projections under the RCP8.5 scenario indicate a progressive intensification of PET, especially during summer. **Figure A.8** (supplementary materials) illustrates the projected annual cycle for 2040–2060 and 2070–2100, showing a steady increase in PET magnitude, with the largest differences observed in summer months (June to August). By the late century, PET reaches its highest projected levels, reinforcing concerns about increased water loss and exacerbated water scarcity risks in the region.

3.2.5. Spatial Distribution of PET Changes

The spatial distribution of mean relative PET changes (%) for 2040–2060 and 2070–2100 is presented in Fig. 7. For 2040–2060, PET is projected to increase by 10–21 %, indicating higher evaporative demand and greater water loss through evaporation and transpiration. By 2070–2100, PET increases become more widespread, with some regions experiencing rises of up to 38 %. These trends suggest an elevated risk of drought conditions, as higher PET, coupled with declining precipitation, may lead to reduced water availability and increased pressure on water resources.

3.2.6. Inter-model variability in PET projections

Future PET projections exhibit considerable variability across climate models. **Figure A.9** (supplementary materials) presents the mean relative change in PET (%) for different models under RCP8.5, comparing mid-century (2040–2060) and late-century (2070–2100) projections. While all models indicate PET increases, the magnitude varies: some models project increases exceeding 30 % by 2070–2100, whereas others suggest more moderate rises.

This variability is further illustrated in **Figure A.10** (supplementary materials), which presents a boxplot of PET changes across basins. For 2040–2060, median increases range between 10 % and 30 %, with some models displaying significant outliers. By 2070–2100, projections show even greater increases and higher inter-model variability, emphasizing the uncertainty in long-term PET projections. These findings underscore the importance of using multi-model ensembles for a robust assessment of climate impacts on evapotranspiration and water availability.

3.2.7. Projected changes in discharge

To assess future river discharge dynamics, we use the HYPE and GR4J-CemaNeige hydrological models, both previously calibrated and validated with CHIRPS precipitation data and ERA5 temperature data. These models are then driven by climate simulations (precipitation and temperature) that have been bias-corrected.

3.2.8. Spatial distribution of discharge changes

The spatial distribution of the mean projected change of the mean annual discharge under RCP8.5 is illustrated in Fig. 8, showing consistent declines across both models for 2040–2060 and 2070–2100.

For 2040–2060, reductions in mean annual discharge range from −20 % to −60 %, with a further intensification by 2070–2100, where declines could reach up to −80 % in certain regions. The HYPE model projects moderate decreases of −10 % to −40 % in 2040–2060, particularly in southwestern basins, but up to −60 % to −80 % in 2070–2100, especially in western basins. Similarly, the GR4J-CemaNeige model projects discharge reductions of −20 % to −40 % in the mid-century period, with more pronounced declines of up to −80 % toward 2100, particularly in central and southwestern regions.

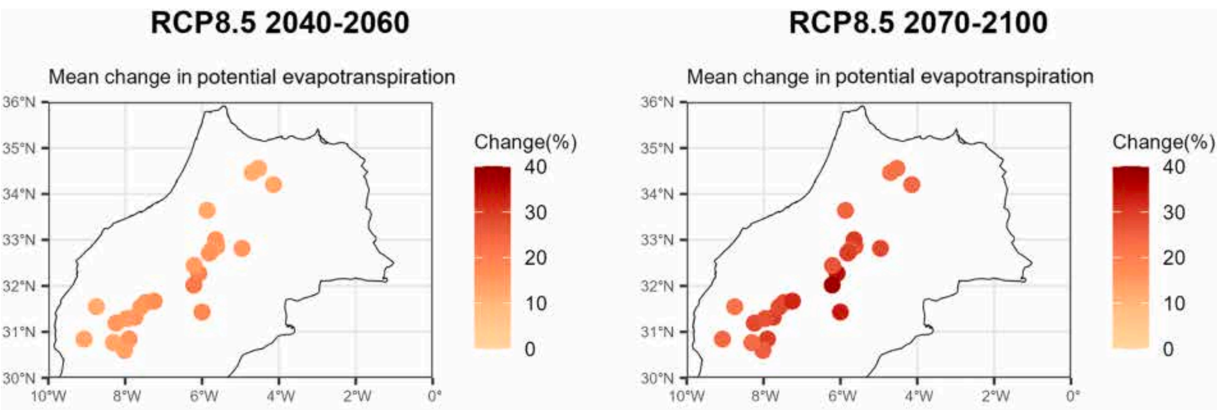

Fig. 7. Spatial Distribution of Mean Relative Change in Potential Evapotranspiration (%) relative to the historical period (1975–2005) for 2040–2060 and 2070–2100.

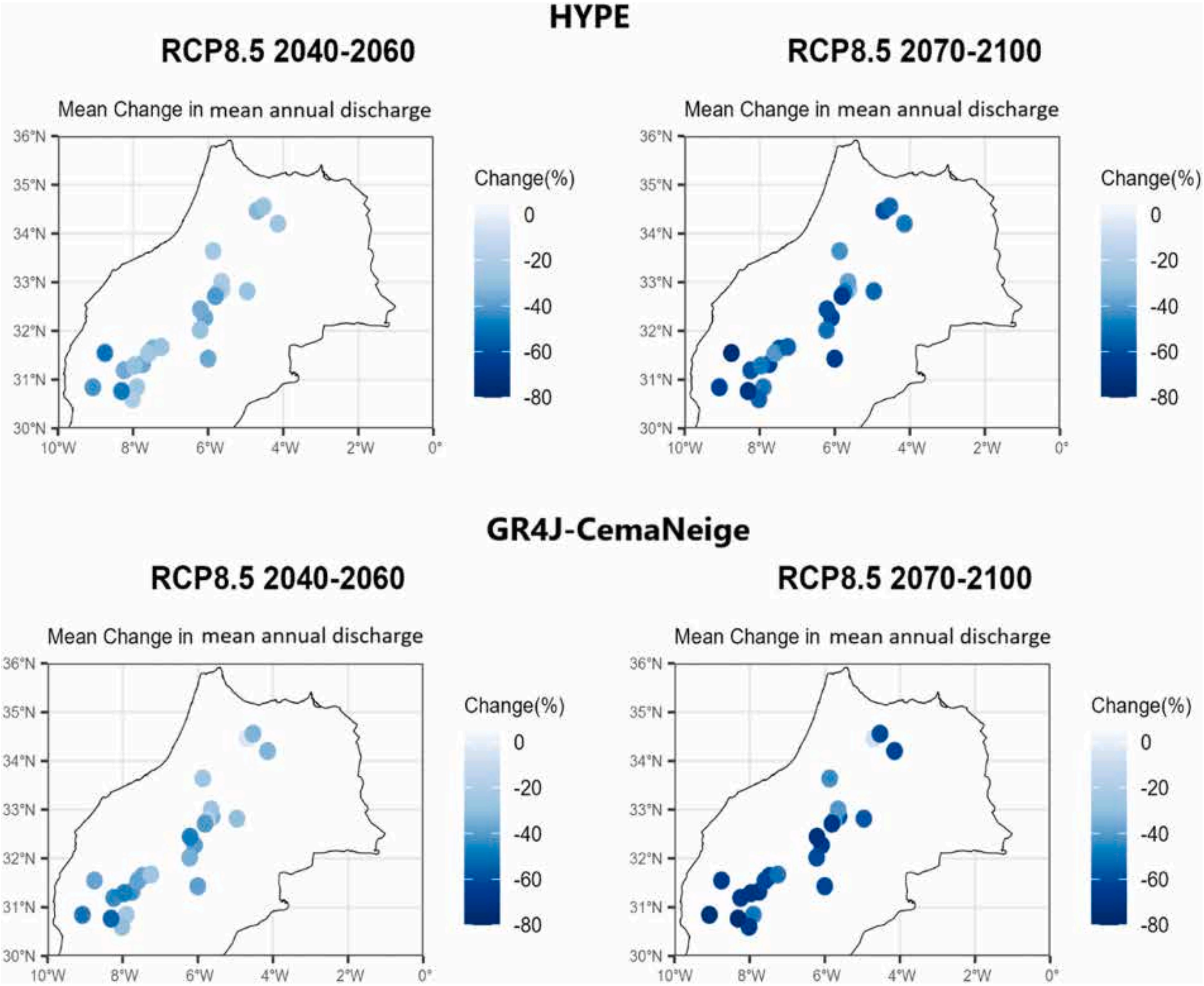

Fig. 8. Spatial Distribution of Relative Change in Mean Discharge (%) for the HYPE and GR4J-CemaNeige Models relative to the historical period (1975–2005) for 2040–2060 and 2070–2100.

3.2.9. Inter-model variability in discharge projections

Projected changes in mean annual discharge across multiple climate models (**Figure A.11**, supplementary materials) show a consistent decline across both hydrological models and future horizons (2040–2060 and 2070–2100). Some models, such as MIROC-MIROC5 and IPSL-CM5A-MR, project reductions exceeding 60 % by 2070–2100, indicating a severe impact of climate change on water resources.

This variability is further illustrated in Fig. 9, which presents a boxplot of projected discharge changes for the HYPE and GR4J-CemaNeige models across basins. For 2040–2060, median reductions range from −20 % to −50 %, depending on the hydrological model and time period. While HYPE exhibits slightly lower variability, both models indicate increased hydrological stress in 2070–2100, emphasizing the need to account for climate and hydrological model uncertainties when assessing future water availability.

The projected decline in discharge, driven by decreasing precipitation and increasing evapotranspiration, underscores the growing vulnerability of water resources under climate change.

3.2.10. Projected changes in Snow

3.2.10.1. Snow storage. The annual cycle of snow storage is illustrated in Fig. 10**,** as simulated by the HYPE and GR4J-CemaNeige hydrological models. These models explicitly account for snow processes, providing insights into snow accumulation and melt dynamics. The mean snow storage across all basins is depicted for each climate model individually and for the ensemble mean of the models.

The results indicate distinct seasonal patterns of snow accumulation, with peak snow storage typically occurring between February and March for both models. Under historical climate conditions, the snow storage simulated by the HYPE model reaches its seasonal

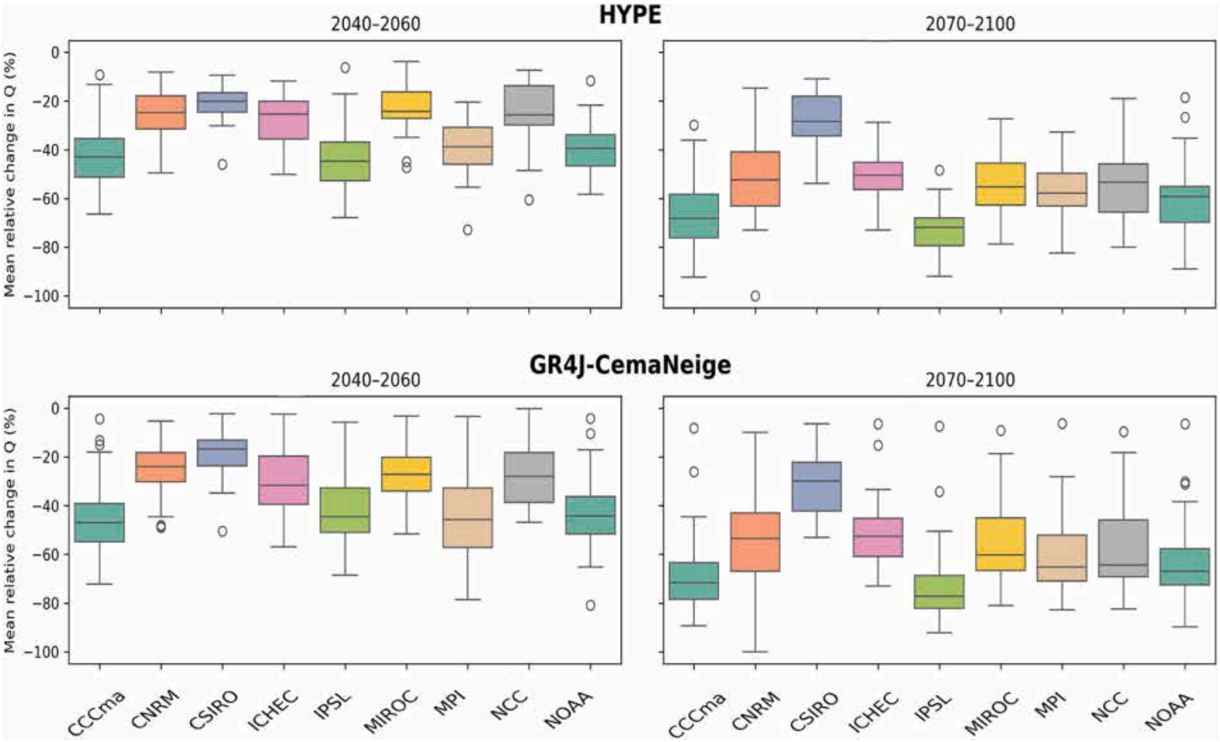

Fig. 9. Boxplot illustrating the change signal in Discharge (Q) for Two Hydrological Models (HYPE and GR4J-CemaNeige) across basins for different climate models under RCP8.5 Scenario.

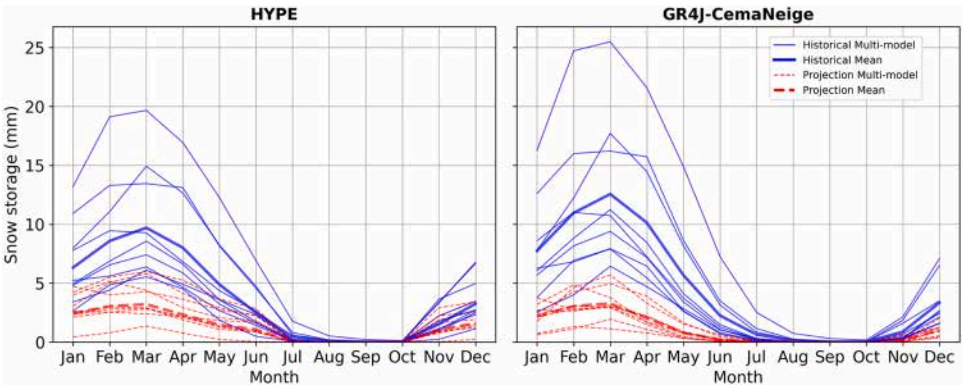

Fig. 10. Annual cycle of snow storage simulated by HYPE and GR4J-CemaNeige models under historical and projected climate conditions across all basins. The lines represent the basin-average snow storage for individual climate models and their ensemble means.

maximum during this period, although it remains lower compared to the values simulated by GR4J-CemaNeige. Snow storage then progressively decreases throughout spring, completely melting by early summer.

Under future climate projections, all climate models consistently project a significant decrease in snow storage. This decline is particularly pronounced during peak snow accumulation months, suggesting warmer temperatures and potentially altered precipitation patterns in the future. The ensemble mean indicates that snow storage could decrease by more than 50 % relative to historical levels. This substantial reduction could result from warmer winter and spring temperatures, leading to a shorter snow accumulation period, earlier melt onset, and reduced overall snowpack. These projected changes in snow dynamics are critical as they imply significant alterations in the hydrological regime, including earlier peak discharge and potential reductions in water availability during the drought season.

3.2.10.2. Snow melt contribution. Fig. 11 illustrates the spatial distribution of snowmelt contribution (%) to discharge for each basin under historical and projected climate scenarios. Fig. 12 presents boxplots comparing snowmelt contributions across different climate

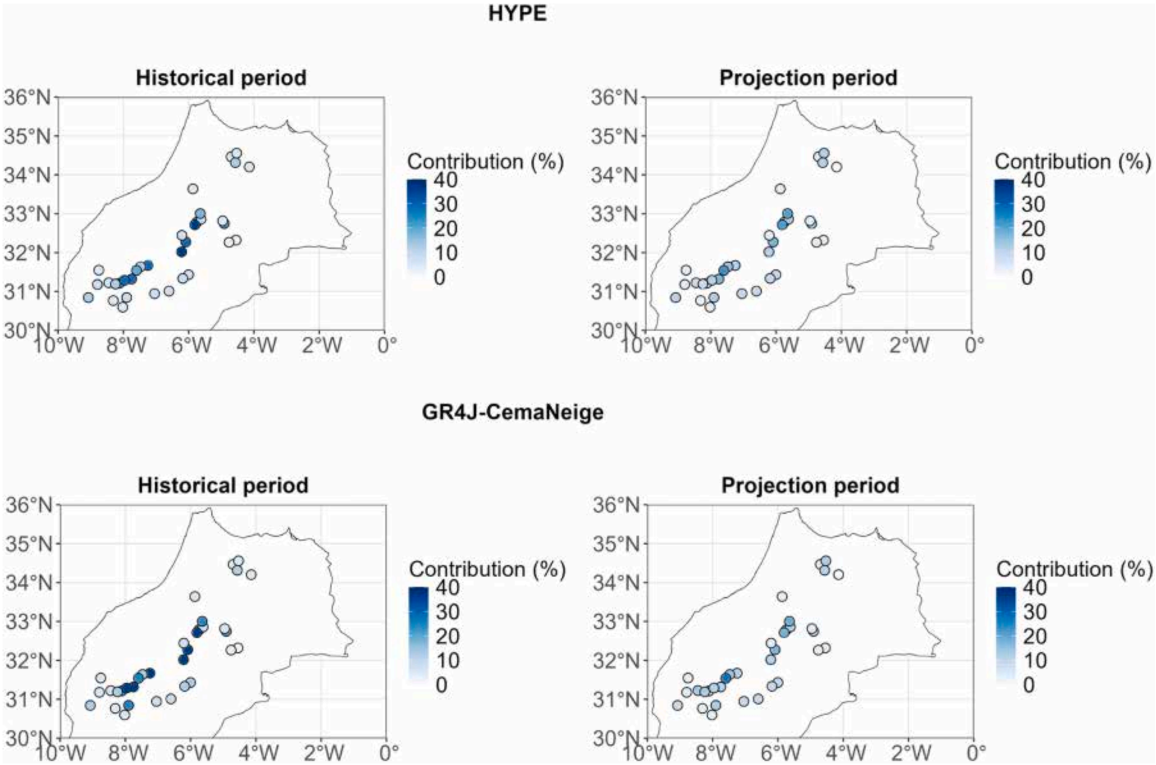

Fig. 11. Spatial distribution maps illustrating the relative contribution (%) of snowmelt to discharge across all basins for historical and projected periods under the HYPE and GR4J-CemaNeige models.

models for the HYPE and GR4J-CemaNeige models during both historical and projected periods.

Historically, snowmelt significantly contributes to discharge, especially in mountainous regions, with contributions frequently reaching around 15 % and occasionally exceeding 30 % in specific basins (Boudhar et al., 2016). However, both the GR4J-CemaNeige and HYPE models tend to overestimate snowmelt contributions compared to these observational estimates. The GR4J-CemaNeige model generally reports slightly higher values than the HYPE model, which can be attributed to differences in the snowmelt parameterization schemes implemented in the two models. This overestimation underscores the importance of accurately representing snow processes in hydrological modeling, particularly in snow-dominated catchments. Under projected climate conditions, snowmelt contributions to discharge exhibit a clear decrease, generally falling below 5 % across most basins. This marked decline signifies a shift towards rainfall-dominated hydrology and highlights the reduced role of snowmelt in future water availability. These spatially coherent patterns highlight substantial alterations in hydrological processes, underscoring the critical need for adaptive water management strategies to mitigate the impacts of projected reductions in snowmelt-driven discharge under future climate warming scenarios.

3.3. Relationships between climatic and hydrological variables

The relationships between climatic changes and hydrological responses under the RCP8.5 scenario (2070–2100) are analyzed by examining changes in precipitation (P), potential evapotranspiration (PET), and discharge (Q) for the HYPE and GR4J-CemaNeige models, **Figure A.12 (**supplementary materials**)** illustrates these correlations. Both models exhibit a strong positive correlation between changes in precipitation and discharge ($R = 0.96$ for HYPE; $R = 0.95$ for GR4J-CemaNeige), indicating that reductions in precipitation are closely associated with substantial decreases in mean annual discharge. Conversely, there is a negative correlation between changes in evapotranspiration and discharge ($R = -0.74$ for HYPE; $R = -0.73$ for GR4J-CemaNeige); suggesting that increased evapotranspiration due to rising temperatures contributes to diminished discharge by enhancing water loss.

These consistent patterns across both models highlight that precipitation is the dominant factor influencing future discharge in the mountainous basins, while evapotranspiration also plays a significant role. The findings underscore the critical impact of projected climate-induced precipitation reductions and evapotranspiration increases on water availability. Incorporating both variables into hydrological assessments is essential for accurate projections and for developing effective water resource management strategies under changing climatic conditions.

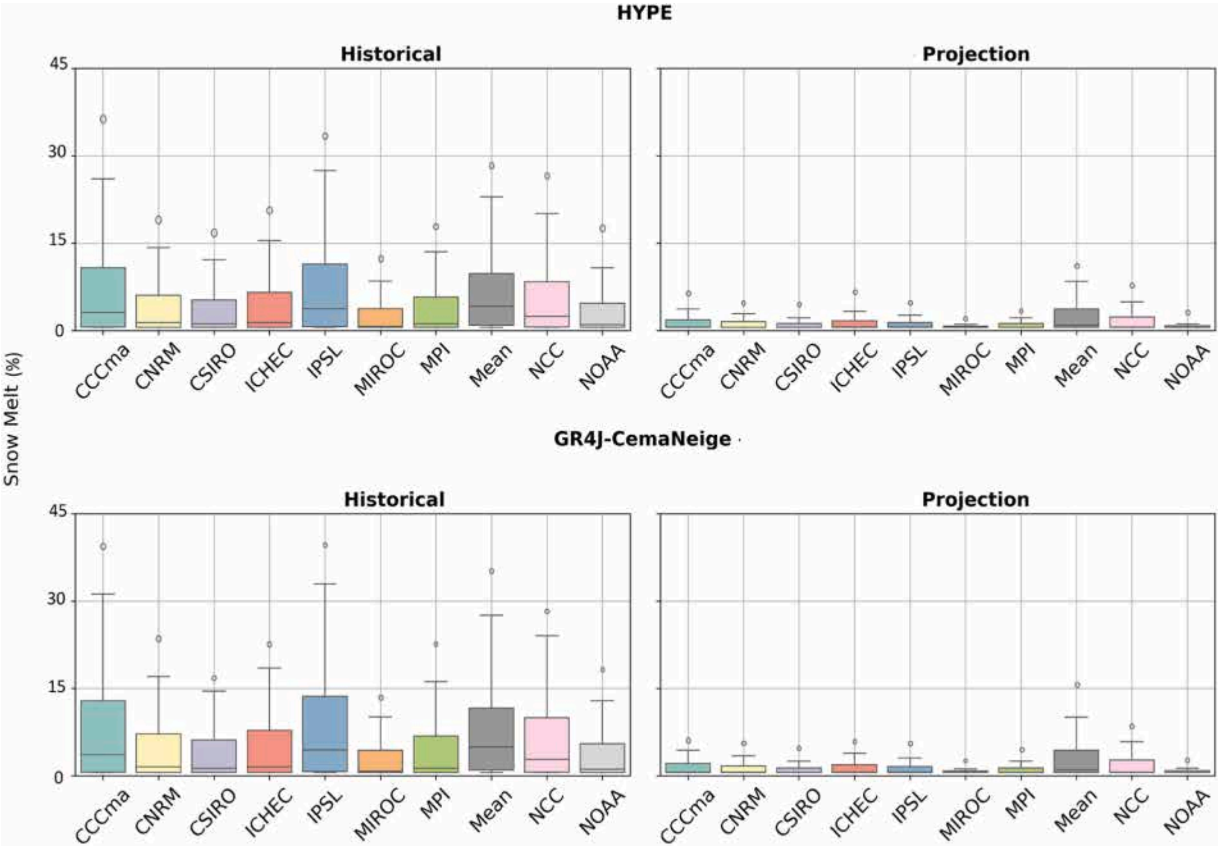

Fig. 12. Boxplots comparing snowmelt Contribution (%) across different climate models for two hydrological models (HYPE and GR4J-CemaNeige) during historical and projected periods.

3.4. Relationships between projected changes and basin characteristics

This section examines how various physical and climatic attributes of the basins influence the projected mean changes in discharge under the RCP8.5 scenario for 2070–2100. Fig. 13 presents a correlation matrix illustrating the relationships between the projected changes in discharge for the HYPE and GR4J-CemaNeige models and several environmental variables.

The analysis indicates that basins with higher aridity index values are projected to experience larger changes in discharge, suggesting that drier regions are more sensitive to alterations in discharge under climate change. This finding highlights how the impacts of climate change manifest differently across basins with varying levels of aridity. Similarly, climatic variables such as mean annual precipitation and potential evapotranspiration exhibit moderate to strong correlations with projected changes, particularly for the HYPE model. This underscores the predominant role of climatic factors in driving hydrological responses under future climate scenarios.

Soil and groundwater characteristics, such as available water capacity and groundwater depth, display weaker or more variable correlations with discharge changes. While these factors influence hydrological responses, their impact appears less pronounced

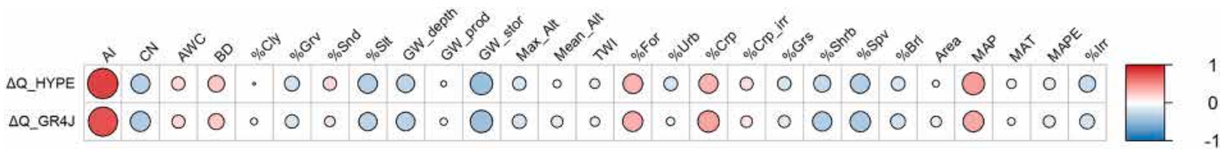

Fig. 13. Correlation Matrix of Mean Changes in Discharge, Precipitation, Evapotranspiration, and Basin Characteristics (RCP8.5, 2070–2100). **Notes:** AI: Aridity Index, CN: Curve Number, AWC: Available Water Capacity, BD: Bulk Density, %Cly: %Clay, %Grv: %Gravel, %Snd: %Sand, %Slt: %Silt, GW_depth: Groundwater Depth, GW_prod: Groundwater Productivity, GW_stor: Groundwater Storage, Max_Alt: Maximum Altitude, Mean_Alt: Mean Altitude, TWI: Topographic Wetness Index, %For: %Forest, %Urb: %Urban, %Crp: %Cropland, %Crp_irr: %Cropland Irrigated, %Grs: % Grassland, %Shrb: %Shrubland, %Spv: %Sparse Vegetation, %Brl: %Bare Land, MAP: Mean Annual Precipitation, MAT: Mean Annual Temperature, MAPE: Mean Annual Potential Evapotranspiration, %Irr: %Irrigation, ΔQ_HYPE: Mean Change in Discharge for HYPE, ΔQ_GR4J: Mean Change in Discharge for GR4J-CemaNeige.

compared to climatic drivers. Land cover attributes, including the percentages of forest, cropland, and irrigated areas, show mixed effects.

Interestingly, the overall correlation patterns between environmental variables and discharge changes are similar for both models in terms of aridity index, mean annual precipitation, and the percentage of sparse land cover. However, notable differences are observed for variables such as urban areas, clay content, and basin area. These discrepancies suggest that HYPE and GR4J-CemaNeige may respond differently to specific processes, potentially due to variations in model structure or parameterization.

This analysis highlights the intricate interactions between basin characteristics and projected hydrological changes under climate change. It underscores the importance of selecting models that can accurately capture these dynamics and adapting them to specific basin conditions. A model tailored to local physiographic attributes enhances the reliability of climate change impact projections on water resources, providing deeper insights into how basin characteristics influence hydrological responses in a changing climate.

3.5. Analysis of hydrological droughts

Under the RCP8.5 scenario, hydrological droughts are projected to intensify significantly. Both the HYPE and GR4J-CemaNeige models project notable increases in the duration and frequency of drought events, alongside discernible shifts in their seasonal

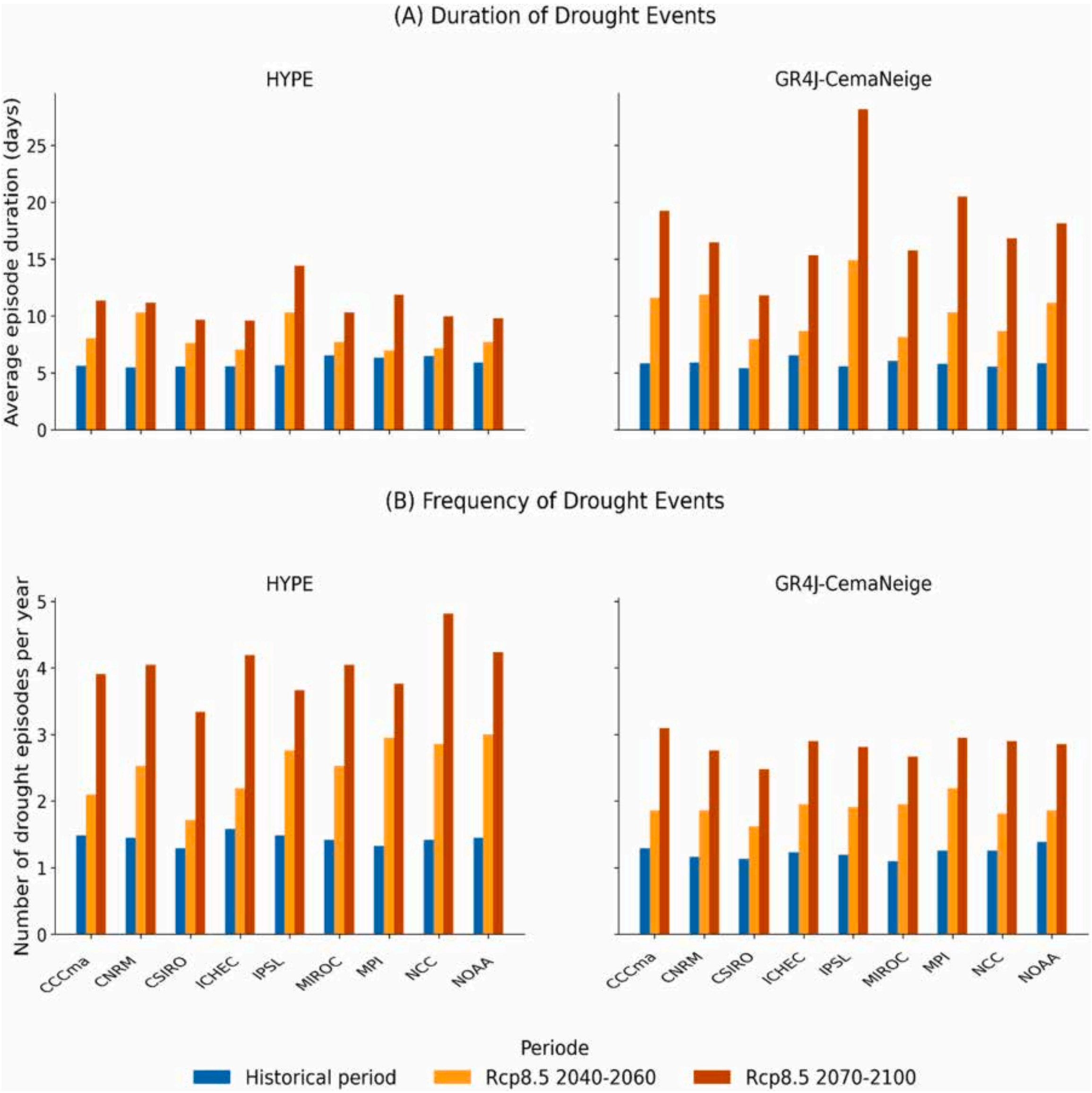

Fig. 14. Projected annual average duration (A) and frequency (B) of drought events for HYPE and GR4J-CemaNeige models under the RCP8.5 scenario, based on the 10th percentile of the 7-day moving average discharge.

patterns during the future periods 2040–2060 and 2070–2100. These findings highlight the escalating risks posed by climate change to water resources in mountainous basins and are detailed below.

3.5.1. Projected increases in drought duration and frequency

The projections reveal a pronounced intensification in the characteristics of drought events. Fig. 14**A** illustrates the projected increase in average drought duration. In the historical period, droughts lasted an average of 5–15 days depending on the hydrological model and basin. Projections for 2040–2060 under the RCP8.5 scenario reveal a near doubling of these durations, with averages ranging between 10 and 25 days. By 2070–2100, drought durations are projected to exceed 20 days on average, with some basins modeled by GR4J-CemaNeige experiencing particularly prolonged events of up to 30 days. These extended durations reflect a significant shift in the hydrological regime of the study region.

In addition to longer durations, the annual frequency of drought events is also expected to rise significantly (Fig. 14**B**). Historically, basins experienced 1–2 drought episodes per year. Projections indicate that by 2040–2060, this number will increase to 2–3 events annually, and by 2070–2100, basins are projected to experience up to 4–5 drought episodes per year based on the range of variability within the climate model ensemble used. The HYPE model projects slightly higher frequencies compared to GR4J-CemaNeige, suggesting and higher sensitivity to climatic variability. Combined with extended durations, this increase in frequency poses significant challenges for water resource management, particularly in basins already experiencing water stress.

The analysis further reveals a strong correlation between drought characteristics and the aridity index of the basins, as illustrated in **Figure A.13 (**supplementary materials**).** Higher aridity is associated with longer drought durations (-0.60 for HYPE and −0.65 for GR4J-CemaNeige) and a greater number of drought episodes (-0.45 for HYPE and −0.50 for GR4J-CemaNeige). These findings indicate that drier basins are more susceptible to intensified drought conditions, driven by a combination of reduced precipitation and higher evapotranspiration rates under future climate scenarios.

3.5.2. Shifts in seasonal occurrence of droughts

Future climate projections reveal significant shifts in the seasonal timing and distribution of drought events, with critical implications for water resources in mountain basins. Historically, droughts have been predominantly concentrated in the summer months, particularly from July to September. However, as shown in Fig. 15, climate change is expected to alter this distribution, with drought events occurring more frequently earlier in the year, March or April and persisting later into October or November. These changes result in a broader temporal spread of droughts, with a notable increase in their frequency during the spring months, especially in April and May.

The projections indicate that by the mid-century period (2040–2060), spring months will experience a marked rise in drought episodes, while by the end of the century (2070–2100), these increases will extend into late autumn (September–October). Additionally, the peak of drought occurrences is expected to shift towards mid-summer, with overall higher drought frequencies compared to the historical baseline.

4. Conclusion

This study assesses the impacts of climate change on discharge in 36 mountainous basins across Morocco, utilizing observed data and climate projections from nine CORDEX-Africa models under the RCP8.5 scenario for the periods 2040–2060 and 2070–2100. Employing the HYPE and GR4J-CemaNeige hydrological models provides valuable insights into projected hydrological responses across diverse basin characteristics.

The evaluation of the two hydrological models shows Kling-Gupta Efficiency (KGE) values between 0,4 and 0,3. The HYPE model consistently demonstrates higher median KGE values compared to GR4J-CemaNeige, suggesting stronger predictive performance across diverse hydrological conditions. Nonetheless, the interpretation of these metrics must consider both the structural limitations of the models and the specific characteristics of the calibration procedures applied. It is important to acknowledge that conceptual hydrological models inherently simplify complex natural catchment dynamics. Consequently, they may not fully capture land-surface energy and water budgets, because they aggregate various processes including soil moisture dynamics, evapotranspiration, and groundwater contributions.

Analysis of projected climatic conditions highlights significant declines in precipitation of up to −43 %, coupled with increases in potential evapotranspiration of up to + 38 % by 2070–2100. These changes exacerbate existing water scarcity challenges, presenting critical implications for sustainable water resource management. Both hydrological models predict notable reductions in mean discharge, with some areas potentially experiencing discharge decreases of up to −80 % by the end of the century. This underscores the severe threat posed by high-emission scenarios to water availability in Morocco's mountainous basins.

Furthermore, snow storage and snowmelt contributions are projected to decline substantially due to rising temperatures. Peak snow storage is expected to decrease by over 50 %, leading to a shift in the hydrological regime from snowmelt-dominated to rainfall-driven discharge regime. This reduction in snowmelt contribution will alter seasonal water availability, reducing discharge during late spring and early summer, when snowmelt historically played a crucial role in sustaining discharge in Morocco. The diminishing snowpack further compounds the risk of extended dry periods, emphasizing the need for climate-adaptive water resource planning in mountainous regions.

In addition to decreasing discharge, hydrological droughts are projected to intensify, characterized by longer durations, increased frequency, and earlier seasonal onset. By 2070–2100, drought events could persist for more than 30 days on average, occurring up to 4–5 times annually. This increase in the severity and duration of drought conditions places substantial pressure on water resources,

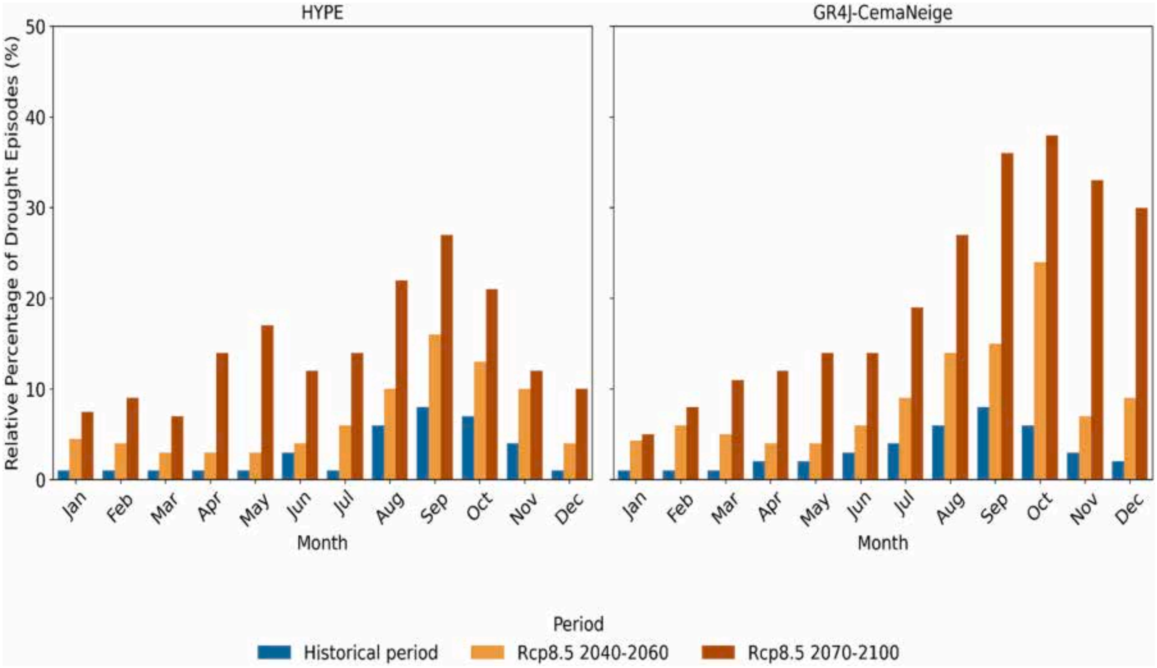

Fig. 15. Monthly distribution of drought episodes across historical and future periods for HYPE and GR4J-CemaNeige models.

heightening the need for adaptive management and mitigation measures to safeguard water security.

The findings of this study emphasize the dominant role of precipitation variability in driving discharge changes, as demonstrated by strong positive correlations (R $\approx$ 0.96) between precipitation decline and discharge reduction. Simultaneously, increased evapotranspiration shows a significant negative correlation (R ≈ -0.74) with discharge, further compounding water loss across the basins. Notably, the impacts are not uniform, with drier basins exhibiting greater sensitivity to hydrological stress. The projected decline in snow storage and snowmelt contribution further amplifies these hydrological changes, requiring integrated water management approaches that account for both precipitation-driven and snowmelt-driven water supply reductions.

Perspectives and recommendations

The projected discharge reductions and intensified drought conditions underscore the heightened vulnerability of water resources in mountainous regions under high-emission scenarios. Longer and more frequent droughts are likely to strain water supplies for agricultural, domestic, and ecological needs. These changes highlight the urgency for developing adaptive water management strategies to mitigate the adverse impacts of climate change on the region's water resources and to ensure sustainable development. Adaptive water management is paramount to optimizing resource utilization and buffering against the variability in water availability. Key strategies include implementing efficient irrigation practices, enhancing water storage infrastructure such as reservoirs and groundwater recharge systems and promoting drought-resistant crop varieties. Additionally, formulating integrated water resource management policies that incorporate climate projections and hydrological modeling is essential. Such policies should prioritize sustainable water allocation, conservation measures, and the development of early warning systems to predict and mitigate drought risks effectively. In the agricultural sector, adaptation measures such as shifting to less water-intensive and drought-resistant crops, adjusting planting schedules, and adopting water-saving technologies are crucial for sustaining productivity under changing climatic conditions. Furthermore, strengthening monitoring and early warning systems by expanding snowpack monitoring and improving seasonal forecasting of precipitation, temperature, and evapotranspiration will enhance drought preparedness and water planning. These approaches not only improve forecasting accuracy but also support the optimization of reservoir management and mitigate the impacts of climate change on mountainous basins.

The shifts in the annual distribution of hydrological drought events pose critical challenges for water resource management in mountain basins. Snowmelt and spring rainfall, which are essential for replenishing surface and groundwater systems, may no longer align with periods of increasing water demand. The earlier onset of droughts coincides with the snowmelt period, potentially disrupting the balance between water supply and demand, particularly for agricultural and domestic needs. Prolonged drought conditions are also likely to reduce discharge levels and groundwater recharge over an extended period, creating water scarcity for irrigation, drinking water supplies, and hydroelectric power generation. The early depletion of snowpacks and soil moisture reserves could weaken ecosystems' ability to withstand extended dry conditions, affecting vegetation and aquatic habitats.

Agriculture, which depends heavily on reliable water availability, may face disruptions to planting schedules and reductions in crop yields as a result of these changing seasonal patterns. To address these challenges, infrastructures such as reservoirs may need to be adapted to accommodate these shifts in water availability. Additionally, integrated water resource management strategies will be essential, focusing on improved forecasting, sustainable water allocation, and measures to enhance ecosystem resilience. These changes in the seasonal distribution of drought events highlight the urgent need for adaptive strategies to ensure the sustainability of water resources in mountain basins under future climate conditions.

To address the uncertainties and complexities of future climatic and hydrological conditions, a broader scenario analysis is needed. Incorporating CMIP6 projections and exploring multiple Shared Socioeconomic Pathways (SSPs) alongside emission scenarios such as RCP4.5 and RCP2.6 will enable a comprehensive assessment of potential outcomes. This broader framework will help evaluate both high- and low-emission trajectories and provide valuable insights into the effectiveness of mitigation efforts.

Enhancing hydrological models to better capture complex processes such as snowmelt dynamics, groundwater interactions, and land-use changes will improve the precision of projections. Investigating the impacts of land-use and land-cover changes on hydrological responses under climate change is also essential to develop integrated strategies for managing land and water resources. Furthermore, integrating socioeconomic variables into hydrological models will facilitate a deeper understanding of the combined effects of climate change and human activities on water resources, supporting the development of holistic adaptation measures.

This study highlights the critical need for integrated water resource management and the development of robust adaptation policies in response to climate change impacts. Demonstrating, the projected hydrological changes in complex mountainous regions provides a foundational understanding that can inform policy decisions, guide resource allocation, and support sustainable development efforts. Proactive measures based on scientific insights are essential to safeguard water resources for future generations and to enhance the resilience of vulnerable communities and ecosystems in the face of a changing climate.

CRediT authorship contribution statement

Lguensat Redouane: Writing – review & editing, Methodology. **Isberg Kristina:** Writing – review & editing, Methodology. **Ben Ahmed Aicha:** Writing – review & editing, Methodology. **Dahn Joel:** Writing – review & editing, Methodology. **Sultan Benjamin:** Writing – review & editing. **LAHNIK OUIAAM:** Writing – original draft, Visualization, Methodology, Conceptualization. **Tramblay Yves:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Hanich Lahoucine:** Writing – review & editing, Writing – original draft, Supervision. **Andersson Jafet C.M.:** Writing – review & editing, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors sincerely acknowledge the financial support provided by the GDRI RHYMA project, the IDEWA PRIMA project, the PRIMA-S2-ALTOS-2018 project, and the French Embassy in Morocco for the French Government Scholarship. We extend our sincere thanks to Pr. Lahcen Benaabidate, Pr. Mohamed El Mehdi Saidi, Pr. Jalal Moustadraf, and Pr. El Mahdi El Khalki for their invaluable assistance in providing essential data for this study. We also express our gratitude to Jörgen Rosberg and Issam Souassi for their technical support and guidance throughout the research process. Their contributions have been instrumental in the successful completion of this work.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102371.

Data availability

Data will be made available on request.

References

Ahmed, J.S., Buizza, R., Dell'Acqua, M., Demissie, T., Pè, M.E., 2024. Evaluation of ERA5 and CHIRPS rainfall estimates against observations across Ethiopia. Meteorol. Atmos. Phys. 136. https://doi.org/10.1007/s00703-024-01008-0.

Alley, R.B., Berntsen, T., Bindoff, N.L., Chidthaisong, A., Friedlingstein, P., Gregory, J.M., Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Chen, Z., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Manning, M., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Qin, D., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Solomon, S., Somerville, R., Stocker, T.F., Stott, P.A., Stouffer, R.J., Whetton, P., Wood, R.A., Wratt, D., Arblaster, J., Brasseur, G., Christensen, J.H., Denman, K. L., Fahey, D.W., Forster, P., Jansen, E., Jones, P.D., Knutti, R., Le Treut, H., Lemke, P., Meehl, G., Mote, P., Randall, D.A., Stone, D.A., Trenberth, K.E., Willebrand, J., Zwiers, F., 2021. IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge. ⟨https://hal.science/hal-0333455⟩.

Andersson, J.C.M., Arheimer, B., Traoré, F., Gustafsson, D., Ali, A., 2017. Process refinements improve a hydrological model concept applied to the Niger River basin. Hydrol. Process 31, 4540–4554. https://doi.org/10.1002/hyp.11376.

Arheimer, B., Dahné, J., Donnelly, C., Lindström, G., Strömqvist, J., 2012. Water and nutrient simulations using the HYPE model for Sweden vs. the Baltic Sea basin - Influence of input-data quality and scale. Hydrol. Res. 43, 315–329. https://doi.org/10.2166/nh.2012.010.

Arheimer, B., Pimentel, R., Isberg, K., Crochemore, L., Andersson, J.C.M., Hasan, A., Pineda, L., 2020. Global catchment modelling using World-Wide HYPE (WWH), open data, and stepwise parameter estimation. Hydrol. Earth Syst. Sci. 24, 535–559. https://doi.org/10.5194/hess-24-535-2020.

Ayar, V., Vrac, M., Mailhot, A., 2021. Ensemble bias correction of climate simulations: preserving internal variability. Nat. Portf. https://doi.org/10.1038/s41598-021.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nat. 2005 438:7066 438 303–309. https://doi.org/10.1038/nature04141.

Beck, H.E., Pan, M., Miralles, D.G., Reichle, R.H., Dorigo, W.A., Hahn, S., Sheffield, J., Karthikeyan, L., Balsamo, G., Parinussa, R.M., van Dijk, A.I.J.M., Du, J., Kimball, J.S., Vergopolan, N., Wood, E.F., 2021. Evaluation of 18 satellite- And model-based soil moisture products using in situ measurements from 826 sensors. Hydrol. Earth Syst. Sci. 25, 17–40. https://doi.org/10.5194/HESS-25-17-2021.

Beniston, M., Stoffel, M., Hill, M., 2011. Impacts of climatic change on water and natural hazards in the Alps: Can current water governance cope with future challenges? Examples from the European "ACQWA" project. Environ. Sci. Policy 14, 734–743. https://doi.org/10.1016/J.ENVSCI.2010.12.009.

Boudhar, A., 2009. Télédétection du manteau neigeux et modélisation de la contribution des eaux de fonte des neiges aux débits des Oueds du Haut Atlas de Marrakech. 〈https://api.semanticscholar.org/CorpusID:131581374〉.

Boudhar, A., Boulet, G., Hanich, L., Sicart, J.E., Chehbouni, A., 2016. Energy fluxes and melt rate of a seasonal snow cover in the Moroccan High Atlas. Hydrol. Sci. J. 61 (5), 931–943. https://doi.org/10.1080/02626667.2014.965173.

Boudhar, A., Hanich, L., Boulet, G., Duchemin, B., Berjamy, B., Chehbouni, A., 2009. Evaluation of the Snowmelt Runoff Model in the Moroccan High Atlas Mountains using two snow-cover estimates. Hydrol. Sci. J. 54, 1094–1113.

Boumenni, H., Bachnou, A., Alaa, N.E., 2017. The rainfall-runoff model GR4J optimization of parameter by genetic algorithms and Gauss-Newton method: application for the watershed Ourika (High Atlas, Morocco). Arab. J. Geosci. 10, 1–12. https://doi.org/10.1007/s12517-017-3086-x.

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W.W.L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, Y.-Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F.E.L., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H.-O., Revi, A., Roberts, D.C., Roy, J., Ruane, A.C., Skea, J., Shukla, P.R., Slade, R., Slangen, A., Sokona, Y., Sörensson, A.A., Tignor, M., van Vuuren, D., Wei, Y.-M., Winkler, H., Zhai, P., Zommers, Z., Hourcade, J.-C., Johnson, F.X., Pachauri, S., Simpson, N.P., Singh, C., Thomas, A., Totin, E., Alegría, A., Armour, K., Bednar-Friedl, B., Blok, K., Cissé, G., Dentener, F., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hansen, G., Hauser, M., Hawkins, E., Hermans, T., Kopp, R., Leprince-Ringuet, N., Lewis, J., Ley, D., Ludden, C., Niamir, L., Nicholls, Z., Some, S., Szopa, S., Trewin, B., van der Wijst, K.-I., Winter, G., Witting, M., Birt, A., Ha, M., 2023. IPCC, 2023: Climate Change 2023: Synthesis Report. In: Lee, H., Romero, J. (Eds.), Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647.

Chaponnière, a, 2005. Fonctionnement hydrologique d'un bassin versant montagneux semi-aride Cas du bassin versant du Rehraya (Haut Atlas marocain). Paris-Grignon [Hydrol. Funct. a 1–268. 〈https://www.discover.ltd.uk/downloads/teaching-resources/the-water-cycle-in-imlil-valley/phd-thesis-rehraya-river.pdf〉.

Christensen, N.S., Lettenmaier, D.P., 2007. Hydrology and Earth System Sciences A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. Hydrol. Earth Syst. Sci. 〈www.hydrol-earth-syst-sci.net/11/1417/2007/〉.

Clark, M.P., Wilby, R.L., Gutmann, E.D., Vano, J.A., Gangopadhyay, S., Wood, A.W., Fowler, H.J., Prudhomme, C., Arnold, J.R., Brekke, L.D., 2016. Characterizing Uncertainty of the Hydrologic Impacts of Climate Change. Curr. Clim. Change Rep. https://doi.org/10.1007/s40641-016-0034-x.

Cook, B.I., Ault, T.R., Smerdon, J.E., 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Sci. Adv. 1. https://doi.org/10.1126/SCIADV.1400082.

Coron, L., Thirel, G., Delaigue, O., Perrin, C., Andréassian, V., 2017. The suite of lumped GR hydrological models in an R package. Environ. Model. Softw. 94, 166–171. https://doi.org/10.1016/J.ENVSOFT.2017.05.002.

De Martonne, E. (1926) Une nouvelle function climatologique: L'indice d'aridité [A New Climatological Function: The Aridity Index]. La Meteorologie, 2, 449-458.

Dembele, M., Schaefli, B., Van De Giesen, N., 2020. Suitability of 17 gridded rainfall and temperature datasets for large-scale hydrological modelling in West Africa. Hydrol. Earth Syst. Sci. 24, 5379–5406. https://doi.org/10.5194/HESS-24-5379-2020.

Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., Ceccato, P., 2018. Validation of the CHIRPS satellite rainfall estimates over eastern Africa. Q. J. R. Meteorol. Soc. 144, 292–312. https://doi.org/10.1002/qj.3244.

Donnelly, C., Andersson, J.C.M., Arheimer, B., 2016. Using flow signatures and catchment similarities to evaluate the E-HYPE multi-basin model across Europe. Hydrol. Sci. J. 61, 255–273. https://doi.org/10.1080/02626667.2015.1027710.

Dosio, A., Jones, R.G., Jack, C., Lennard, C., Nikulin, G., Hewitson, B., 2019. What can we know about future precipitation in Africa? Robustness, significance and added value of projections from a large ensemble of regional climate models. Clim. Dyn. 53, 5833–5858. https://doi.org/10.1007/s00382-019-04900-3.

Dosio, A., Panitz, H.J., Schubert-Frisius, M., Lüthi, D., 2015. Dynamical downscaling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the present climate and analysis of the added value. Clim. Dyn. 44, 2637–2661. https://doi.org/10.1007/s00382-014-2262-x.

El Khalki, E.M., Tramblay, Y., Hanich, L., Marchane, A., Boudhar, A., Hakkani, B., 2021. Climate change impacts on surface water resources in the Oued El Abid basin, Morocco. Hydrol. Sci. J. 66, 2132–2145. https://doi.org/10.1080/02626667.2021.1982137.

Famien, A.M., Janicot, S., Delfin Ochou, A., Vrac, M., Defrance, D., Sultan, B., Noël, T., 2018. A bias-corrected CMIP5 dataset for Africa using the CDF-t method - A contribution to agricultural impact studies. Earth Syst. Dyn. 9, 313–338. https://doi.org/10.5194/esd-9-313-2018.

Fatichi, S., Vivoni, E.R., Ogden, F.L., Ivanov, V.Y., Mirus, B., Gochis, D., Downer, C.W., Camporese, M., Davison, J.H., Ebel, B., Jones, N., Kim, J., Mascaro, G., Niswonger, R., Restrepo, P., Rigon, R., Shen, C., Sulis, M., Tarboton, D., 2016. An overview of current applications, challenges, and future trends in distributed process-based models in hydrology. J. Hydrol. (Amst.). https://doi.org/10.1016/j.jhydrol.2016.03.026.

Filahi, S., Tramblay, Y., Mouhir, L., Diaconescu, E.P., 2017. Projected changes in temperature and precipitation indices in Morocco from high-resolution regional climate models. Int. J. Climatol. 37, 4846–4863. https://doi.org/10.1002/JOC.5127.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. Sci. Data 2. https://doi.org/10.1038/SDATA.2015.66.

García-Ruiz, J.M., López-Moreno, I.I., Vicente-Serrano, S.M., Lasanta-Martínez, T., Beguería, S., 2011. Mediterranean water resources in a global change scenario. Earth Sci. Rev. 105, 121–139. https://doi.org/10.1016/J.EARSCIREV.2011.01.006.

Gascoin, S., 2021. Snowmelt and snow sublimation in the indus basin. Water (Switz.) 13. https://doi.org/10.3390/w13192621.

Gebrechorkos, S.H., Leyland, J., Dadson, S.J., Cohen, S., Slater, L., Wortmann, M., Ashworth, P.J., Bennett, G.L., Boothroyd, R., Cloke, H., Delorme, P., Griffith, H., Hardy, R., Hawker, L., McLelland, S., Neal, J., Nicholas, A., Tatem, A.J., Vahidi, E., Liu, Y., Sheffield, J., Parsons, D.R., Darby, S.E., 2024. Global-scale evaluation of precipitation datasets for hydrological modelling. Hydrol. Earth Syst. Sci. 28, 3099–3118. https://doi.org/10.5194/hess-28-3099-2024.

Gelfan, A., Gustafsson, D., Motovilov, Y., Arheimer, B., Kalugin, A., Krylenko, I., Lavrenov, A., 2017. Climate change impact on the water regime of two great Arctic rivers: modeling and uncertainty issues. Clim. Change 141, 499–515. https://doi.org/10.1007/s10584-016-1710-5.

Giorgi, F., Jones, C., Asrar, G.R., 2009. Addressing climate information needs at the regional level: the CORDEX framework. WMO Bull. 〈https://cordex.org/wp-content/uploads/2012/11/cordex_giorgi_wmo-1.pdf〉.

Giuntoli, I., Vidal, J.-P., Prudhomme, C., Hannah, D.M., 2015. Future hydrological extremes: the uncertainty from multiple global climate and global hydrological models. Earth Syst. Dynam. 6, 267–285. https://doi.org/10.5194/esd-6-267-2015.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps-a review. Sci. Total Environ. 493, 1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050.

Gosling, S.N., Zaherpour, J., Mount, N.J., Hattermann, F.F., Dankers, R., Arheimer, B., Breuer, L., Ding, J., Haddeland, I., Kumar, R., Kundu, D., Liu, J., van Griensven, A., Veldkamp, T.I.E., Vetter, T., Wang, X., Zhang, X., 2017. A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1 °C, 2 °C and 3 °C. Clim. Change 141, 577–595. https://doi.org/10.1007/s10584-016-1773-3.

Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. J. Hydrol. (Amst.) 377, 80–91. https://doi.org/10.1016/J.JHYDROL.2009.08.003.
Hajhouji, Y., Fakir, Y., Simonneaux, V., Gascoin, S., Bouras, E.H., Chehbouni, A., 2020. Effects of climate change at the 2040's horizon on the hydrology of the Pluvio-Nival Rheraya Watershed Near Marrakesh, Morocco (LNEE). Lect. Notes Electr. Eng. 684, 440–450. https://doi.org/10.1007/978-3-030-53187-4_48.
Hajhouji, Y., Simonneaux, V., Gascoin, S., Fakir, Y., Richard, B., Chehbouni, A., Boudhar, A., 2018. Modélisation pluie-débit et analyse du régime d'un bassin versant semi-aride sous influence nivale. Cas du bassin versant du Rheraya (Haut Atlas, Maroc). La Houille Blanc 49–62. https://doi.org/10.1051/LHB/2018032.
Hanich, L., Chehbouni, A., Gascoin, S., Boudhar, A., Jarlan, L., Tramblay, Y., Boulet, G., Marchane, A., Baba, M.W., Kinnard, C., Simonneaux, V., Fakir, Y., Bouchaou, L., Leblanc, M., Le Page, M., Bouamri, H., Er-Raki, S., Khabba, S., 2022. Snow hydrology in the Moroccan atlas mountains. J. Hydrol. Reg. Stud. 42, 101101. https://doi.org/10.1016/j.ejrh.2022.101101.
Hanich, L., Lahnik, O., Gascoin, S., Chakir, A., Simonneaux, V., 2024. Quantifying snow sublimation by Eddy covariance measurements on the High Atlas Mountain of Marrakech at Tazaghart plateau, Morocco. Proc. Int. Assoc. Hydrol. Sci. Copernic. Publ. 387–391. https://doi.org/10.5194/piahs-385-387-2024.
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.N., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146, 1999–2049. https://doi.org/10.1002/qj.3803.
Hisdal, H., Tallaksen, L., ARIDE, E.P., 2000. Drought event definition. ARIDE. ⟨https://www.droughtmanagement.info/literature/UNIVERSITYofOSLO_Drought_Event_Definition_2000.pdf⟩.
Hodgkins, G.A., Renard, B., Whitfield, P.H., Laaha, G., Stahl, K., Hannaford, J., Burn, D.H., Westra, S., Fleig, A.K., Araújo Lopes, W.T., Murphy, C., Mediero, L., Hanel, M., 2024. Climate driven trends in historical extreme low streamflows on four continents. Water Resour. Res. 60. https://doi.org/10.1029/2022WR034326.
Huss, M., Hock, R., 2018. Global-scale hydrological response to future glacier mass loss. Nat. Clim. Change 8, 135–140. https://doi.org/10.1038/s41558-017-0049-x.
Immerzeel, W.W., Van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate change will affect the asian water towers. Science 328 (1979), 1382–1385. https://doi.org/10.1126/science.1183188.
Jiao, D., Xu, N., Yang, F., Xu, K., 2021. Evaluation of spatial-temporal variation performance of ERA5 precipitation data in China. Sci. Rep. 11, 1–13. https://doi.org/10.1038/s41598-021-97432-y.
Katsanos, D., Retalis, A., Michaelides, S., 2016. Validation of a high-resolution precipitation database (CHIRPS) over Cyprus for a 30-year period. Atmos. Res. 169, 459–464. https://doi.org/10.1016/J.ATMOSRES.2015.05.015.
Kreamer, D.K., 2012. Water and international security. J. Conte Water Res. Educ. 149, 1–3. https://doi.org/10.1111/J.1936-704X.2012.03121.X.
Kusangaya, S., Warburton, M.L., Archer van Garderen, E., Jewitt, G.P.W., 2014. Impacts of climate change on water resources in southern Africa: a review. Phys. Chem. Earth, Parts A/B/C 47–54. https://doi.org/10.1016/J.PCE.2013.09.014.
Lavers, D.A., Simmons, A., Vamborg, F., Rodwell, M.J., 2022. An evaluation of ERA5 precipitation for climate monitoring. Q. J. R. Meteorol. Soc. 148, 3152–3165. https://doi.org/10.1002/QJ.4351.
Liu, D., Guo, S., Wang, Z., Liu, P., Yu, X., Zhao, Q., Zou, H., 2018. Statistics for sample splitting for the calibration and validation of hydrological models. Stoch. Environ. Res. Risk Assess. 32, 3099–3116. https://doi.org/10.1007/s00477-018-1539-8.
Luo, Y., Zhang, K., Wang, W., Chen, X., Feng, J., Wang, H., Liu, W., Guo, C., Chen, C., Wang, X., 2025. An improved statistical bias correction method for Global Climate Model (GCM) precipitation projection: a case study on the CMCC-CM2-SR5 model projection in China's Huaihe River Basin. J. Hydrol. Reg. Stud. 57. https://doi.org/10.1016/j.ejrh.2024.102146.
Marchane, A., Jarlan, L., Hanich, L., Boudhar, A., 2014. Caractérisation de l'enneigement sur l'atlas marocain par le capteur MODIS et relation avec le climat (période 2000-2011). Rev. Française De. Photo étrie Et. De. TéléD. étection 13–22. https://doi.org/10.52638/rfpt.2013.18.
Marchane, A., Tramblay, Y., Hanich, L., Ruelland, D., Jarlan, L., 2017. Climate change impacts on surface water resources in the Rheraya catchment (High Atlas, Morocco). Hydrol. Sci. J. 62, 979–995. https://doi.org/10.1080/02626667.2017.1283042.
Mcfarlane, N., 2011. Parameterizations: Representing key processes in climate models without resolving them. Wiley Inter. Rev. Clim. Change 2, 482–497. https://doi.org/10.1002/WCC.122.
Michelangeli, P.A., Vrac, M., Loukos, H., 2009. Probabilistic downscaling approaches: Application to wind cumulative distribution functions. Geophys. Res. Lett. 36. https://doi.org/10.1029/2009GL038401.
Mouelhi, S., Aux, D.E.S.E., Des, E.T., 2004. Vers une chaîne cohérente de modèles pluie-débit aux pas de temps pluriannue, annuel, mensuel et journalier. ⟨https://pastel.hal.science/tel-00005696v1/file/tel-00005696.pdf⟩.
Mouelhi, S., Michel, C., Perrin, C., Andréassian, V., 2006. Stepwise development of a two-parameter monthly water balance model. J. Hydrol. (Amst.) 318, 200–214. https://doi.org/10.1016/j.jhydrol.2005.06.014.
Muerth, M.J., Gauvin St-Denis, B., Ricard, S., Velázquez, J.A., Schmid, J., Minville, M., Caya, D., Chaumont, D., Ludwig, R., Turcotte, R., 2013. On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. Hydrol. Earth Syst. Sci. 17, 1189–1204. https://doi.org/10.5194/hess-17-1189-2013.
Nikulin, G., Jones, C., Giorgi, F., Asrar, G., Büchner, M., Cerezo-Mota, R., Christensen, O.B., Déqué, M., Fernandez, J., Hänsler, A., van Meijgaard, E., Samuelsson, P., Sylla, M.B., Sushama, L., 2012. Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations. J. Clim. 25, 6057–6078. https://doi.org/10.1175/JCLI-D-11-00375.1.
O'Connell, P.E., Todini, E., 1996. Modelling of rainfall, flow and mass transport in hydrological systems: an overview. J. Hydrol. (Amst.) 175, 3–16. https://doi.org/10.1016/S0022-1694(96)80003-5.
Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F., Loumagne, C., 2005. Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2 - Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling. J. Hydrol. 303 (1–4), 290–306. https://doi.org/10.1016/j.jhydrol.2004.08.026.
Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q.D., Dasqupta, P., Dubash, N.K., Edenhofer, O., Elgizouli, I., Field, C.B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Cisneros, B.J., Kattsov, V., Lee, H., Mach, K.J., Marotzke, J., Mastrandrea, M.D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J.J., Pichs-Madruga, R., Plattner, G.-K., Pörtner, H.-O., Power, S.B., Preston, B., Ravindranath, N.H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T.F., Tschakert, P., Vuuren, D. van, Ypersele, J.-P. van, 2014. Climate change 2014 synthesis report. contribution of working groups I, II, and III to the fifth assessment report of the Intergovernmental Panel on Climate Change, Ipcc. IPCC. ⟨https://research-repository.uwa.edu.au/en/publications/climate-change-2014-synthesis-report-contribution-of-working-grou⟩.
Pechlivanidis, I.G., Arheimer, B., 2015. Large-scale hydrological modelling by using modified PUB recommendations: the India-HYPE case. Hydrol. Earth Syst. Sci. 19, 4559–4579. https://doi.org/10.5194/hess-19-4559-2015.
Pechlivanidis, I.G., Bosshard, T., Spångmyr, H., Lindström, G., Gustafsson, D., Arheimer, B., 2014. Uncertainty in the Swedish Operational Hydrological Forecasting Systems, in: Vulnerability, Uncertainty, and Risk: Quantification, Mitigation, and Management - Proceedings of the 2nd International Conference on Vulnerability and Risk Analysis and Management, ICVRAM 2014 and the 6th International Symposium on Uncertainty Modeling a. pp. 253–262. https://doi.org/10.1061/9780784413609.026.
Perrin, C., 2002. Vers une amélioration d'un modèle global pluie-débit au travers d'une approche comparative. La Houille Blanc 88, 84–91. https://doi.org/10.1051/lhb/2002089.
Perrin, C., Michel, C., Andréassian, V., 2003. Improvement of a parsimonious model for streamflow simulation. J. Hydrol. (Amst.) 279, 275–289. https://doi.org/10.1016/S0022-1694(03)00225-7.

Robin, Y., Vrac, M., 2021. Is time a variable like the others in multivariate statistical downscaling and bias correction? Earth Syst. Dyn. 12, 1253–1273. https://doi.org/10.5194/esd-12-1253-2021.

Schilling, J., Freier, K.P., Hertig, E., Scheffran, J., 2012. Climate change, vulnerability and adaptation in North Africa with focus on Morocco. Agric. Ecosyst. Environ. 156, 12–26. https://doi.org/10.1016/J.AGEE.2012.04.021.

Schilling, J., Hertig, E., Tramblay, Y., Scheffran, J., 2020. Climate change vulnerability, water resources and social implications in North Africa. Reg. Environ. Change 20, 1–12. https://doi.org/10.1007/s10113-020-01597-7.

Shindell, D., Bréon, F., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P., 2013. Anthropogenic and Natural Radiative Forc-ing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I. ⟨https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf⟩.

Smakhtin, V.U., 2001. Low flow hydrology: a review. J. Hydrol. (Amst.) 240, 147–186. https://doi.org/10.1016/S0022-1694(00)00340-1.

Stocker, T.F., 2013. a report of Working Group I of the IPCC, technical summary, a report accepted by Working Group I of the IPCC but not approved in detail and frequently asked questions: part of the Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. Clim. Change 2013: Phys. Sci. Basis: Summ. Policy. ⟨https://www.ipcc.ch/site/assets/uploads/2018/03/WG1AR5_SummaryVolume_FINAL.pdf⟩.

Strömqvist, J., Arheimer, B., Dahné, J., Donnelly, C., Lindström, G., 2012. Prévisions des débits et des nutriments dans les bassins non jaugés: mise en place et évaluation d'un modèle à l'échelle nationale. Hydrol. Sci. J. 57, 229–247. https://doi.org/10.1080/02626667.2011.637497.

Tallaksen, L.M., Lanen, H.A.J. van, 2004. Hydrological drought. Processes and estimation methods for streamflow and groundwater. Elsevier. In: ⟨https://research.wur.nl/en/publications/hydrological-drought-processes-and-estimation-methods-for-streamf⟩.

Tramblay, Y., Llasat, M.C., Randin, C., Coppola, E., 2020. Climate change impacts on water resources in the Mediterranean. Reg. Environ. Change 20, 4–6. https://doi.org/10.1007/s10113-020-01665-y.

Tramblay, Y., Ruelland, D., Somot, S., Bouaicha, R., Servat, E., 2013. High-resolution Med-CORDEX regional climate model simulations for hydrological impact studies: a first evaluation of the ALADIN-Climate model in Morocco. Hydrol. Earth Syst. Sci. 17, 3721–3739. https://doi.org/10.5194/hess-17-3721-2013.

Tramblay, Y., Somot, S., 2018. Future evolution of extreme precipitation in the Mediterranean. Clim. Change 151, 289–302. https://doi.org/10.1007/s10584-018-2300-5.

Trenberth, K.E., Dai, A., Van Der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2013. Global warming and changes in drought. Nat. Clim. Change 4, 17–22. https://doi.org/10.1038/nclimate2067.

Trenberth, K.E., Jones, P.D., Ambenje, Peter, Bojariu, Roxana, Easterling, David, Klein Tank, Albert, Parker, David, Rahimzadeh, Fatemeh, Renwick, J.A., Rusticucci, Matilde, Soden, Brian, Zhai, Panmao, Hoskins, B.J., Karl, T.R., Jones, P., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J., Rusticucci, M., Soden, B., Zhai, P., 2007. Observations: Surface and Atmospheric Climate Change.

Tuel, A., El Moçayd, N., Hasnaoui, M.D., Eltahir, E.A.B., 2022. Future projections of High Atlas snowpack and runoff under climate change. Hydrol. Earth Syst. Sci. 26, 571–588. https://doi.org/10.5194/hess-26-571-2022.

Vetter, T., Reinhardt, J., Flörke, M., van Griensven, A., Hattermann, F., Huang, S., Koch, H., Pechlivanidis, I.G., Plötner, S., Seidou, O., Su, B., Vervoort, R.W., Krysanova, V., 2017. Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. Clim. Change 141, 419–433. https://doi.org/10.1007/s10584-016-1794-y.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289 (1979), 284–288. In: ⟨https://research.wur.nl/en/publications/hydrological-drought-processes-and-estimation-methods-for-streamf⟩.

Vrac, M., Noël, T., Vautard, R., 2016. Bias correction of precipitation through singularity stochastic removal: because occurrences matter. J. Geophys. Res.: Atmos. 121. https://doi.org/10.1002/2015JD024511.

Zhu, L., Kang, W., Li, W., Luo, J.J., Zhu, Y., 2022a. The optimal bias correction for daily extreme precipitation indices over the Yangtze-Huaihe River Basin, insight from BCC-CSM1.1-m. Atmos. Res. 271. https://doi.org/10.1016/j.atmosres.2022.106101.