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Impacts of rainfall variability on water resources in the upper Medjerda watershed under semi-arid conditions

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Abstract

This study focuses on the in-depth assessment of the spatio-temporal variability of rainfall in the Upper Medjerda Valley and its direct impact on the hydrological response of the watershed. To this end, a rainfall database spanning from the hydrological year 1980/1981 to 2014/2015 was compiled, gathering the average time series of 16 rain gauges strategically distributed across the studied basin. Missing data, inherent in any long-term collection, were systematically reconstructed using a weighting method, thus ensuring the integrity and continuity of the series. Subsequently, a rigorous statistical analysis was conducted to detect significant breaks in each individual rainfall time series. Three statistically robust tests – Pettitt, SNHT (Standard Normal Homogeneity Test) and Buishand – were applied using XLstat software. These tests, combined with the detailed calculation of specific rainfall indices, highlighted a pronounced alternation of wet and dry episodes, characterized by occurrences of very high rainfall excesses, thus highlighting the complex dynamics of the region's rainfall regime. The next step consisted of a spatial interpolation of rainfall, carried out at different time scales: annual, monthly and seasonal. Three geostatistical and deterministic interpolation methods were used to ensure robustness of the results: the Theissen polygon, splines and ordinary kriging. The average rainfall maps thus generated for the Upper Medjerda Valley then served as an essential basis for the hydrological study. Finally, the study focused on examining the variation of hydrological contributions, establishing their quantitative relationship with rainfall, and assessing their crucial importance for the basin. This was achieved through the implementation of the conceptual hydrological model GR2m. It has been shown that runoff, and by extension, available water resources, constitute the direct and fundamental hydrological response of the watershed to rainfall events, highlighting the close interdependence between precipitation patterns and water availability.

Keywords: Average precipitation, Hydrological behavior, Spatial and temporal variability, Statistical analysis, Upper Medjerda valley.

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1. Introduction

The phenomenon of climate change is now an undeniable reality, whose impact is felt in many areas of our daily lives. Faced with this situation, experts face a crucial task: to alert humanity to the urgent need for sustainable management of natural resources (Hamza et al., 2020; Muhamya et al., 2024). These resources are increasingly threatened by the gradual disappearance, a significant reduction in their quantity, or a substantial deterioration in their quality (Abdulhameed et al., 2021; Wassie, 2020). In this global context, the influence of spatial variability in water withdrawals on the hydrological modeling of river flows represents a major and particularly dynamic area of research, as evidenced by the abundance of scientific literature published in recent years on the subject (d'Odorico et al., 2019; Mhmood et al., 2023). Tunisia's bioclimate exhibits remarkable diversity, ranging from subhumid conditions in the northern regions to fully Saharan characteristics in the south of the country (Boudries-Kaci et al., 2019; Rouissi et al., 2024). Particularly in northern Tunisia, abstraction regimes are characterized by extremely high variability, both in time and space (Abidi et al., 2018). The Upper Medjerda Valley, which falls within this geographical area, is a region where flooding events are very frequent. This vulnerability is explained by a combination of natural and anthropogenic factors, including the rugged terrain, the specificities of the climate, the river's morphology, and land use patterns, among others (Allan, 2004; Naylor et al., 2017).

Accurately quantifying the different components of hydrological processes within a watershed represents a major scientific and practical challenge (Eryiğit & Sulaiman, 2022; Wei et al., 2013). The hydrological system is, indeed, a complex whole, constantly modulated and altered by a multitude of factors, whether internal to the basin (such as geology, pedology, vegetation) or external (such as abstraction, temperature, and human activity). In this context, watershed models have become indispensable and powerful tools for understanding, simulating, and anticipating the dynamic behavior of a watershed under the influence of these interactive processes (Hà, 2025; Wang et al., 2023).

Our work is framed within this general context. It has a dual objective: first, to comprehensively characterize the spatiotemporal variability of water withdrawals in the Upper Medjerda Valley; and second, to deepen our understanding of the complex and multifaceted interactions that exist between the spatiotemporal resolution of water withdrawal data, the inherent variability in the physical properties of the watershed, and the way these elements are represented and integrated into hydrological models. To achieve these ambitious objectives, we selected and applied a simple but effective conceptual rainfall-runoff transformation model: the GR2m model (Kourtis et al., 2025).

2. Materials and methods

2.1. Presentation of the study area: The upper Medjerda valley

The study area for this research is the Upper Medjerda Valley watershed, a major geographical and hydrological entity located in the northeastern part of Tunisia. This basin is specifically located within the Tunisian Upper Tell physiographic region, characterized by varied topography and specific climatic conditions. With

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a total area of approximately 9,238 km², it represents a significant territory on a national scale (Benrhouma et al., 2024).

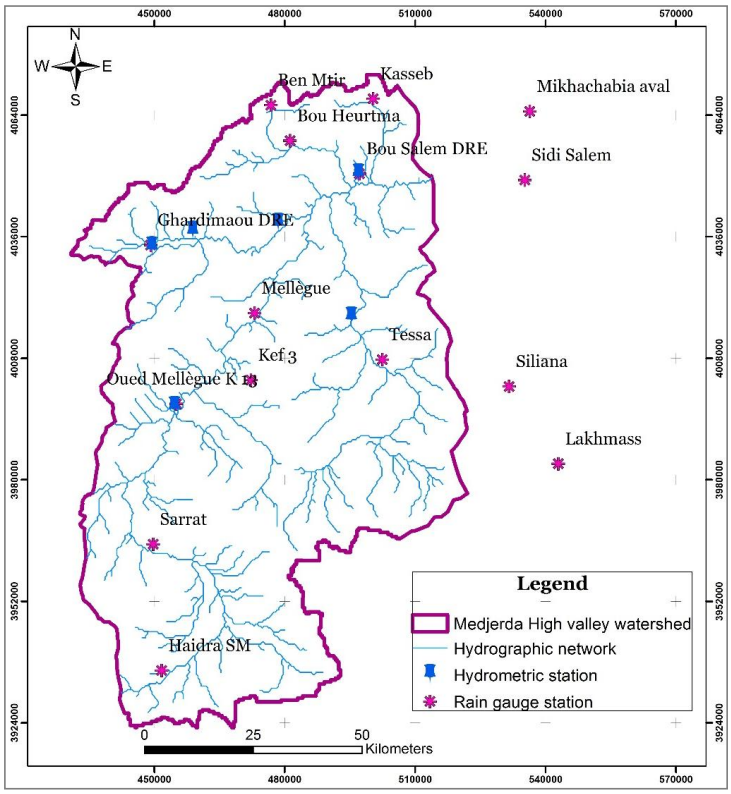

Fig. 1. Map location of the studied area

From a morphological perspective, the Upper Medjerda Valley basin is described as elongated, with a generally high relief. This topographic configuration has a major influence on surface runoff, precipitation distribution, and general hydrological dynamics. The prevailing climate is semi-arid, characterized by often irregular rainfall and marked periods of drought, making the study of rainfall variability all the more relevant for water resource management. The environmental characteristics of this region, combining pronounced relief and variable rainfall, make it a territory particularly exposed to extreme hydrological phenomena, particularly floods and floods.

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3. Results

3.1. Variation in mean precipitation and optimization of spatial interpolation

Analysis of spatial interpolation of precipitation in the Upper Medjerda Valley revealed remarkable variability in mean precipitation using three distinct methods: the Theissen polygon, ordinary kriging, and the spline method. Each of these methods provided a spatial representation of mean annual precipitation, illustrating heterogeneities within the basin.

After determining rainfall averages using these three spatial interpolation methods, a comparative evaluation of their performance was undertaken. This evaluation was based on two key statistical criteria: root mean square error (RMSE) and mean absolute percentage error (MAPE). The results of this comparison clearly indicated that the ordinary kriging method is the most suitable and efficient method for calculating spatially averaged precipitation in the Upper Medjerda Valley. This method was therefore selected as the optimal method for subsequent studies.

3.2. Hydrological response modeling with GR2M

After characterizing precipitation, the study focused on analyzing the hydrological regime of the upper Medjerda basin using the GR2M hydrological model. The model calibration phase was successfully completed, with a Nash coefficient of 60%. This coefficient, greater than 50%, indicates a good match between the simulated flows and the flows observed during the calibration period. The optimized model parameters are as follows:

Parameter X1, representing the model's production reservoir capacity, was calibrated at 5.19. Parameter X2, the exchange coefficient characterizing water gains or losses in the basin, was set at 1.38. An X2 value greater than 1, as is the case here, suggests a net water gain for the basin, potentially due to external inputs or specific transfer processes.

The model validation phase was then launched for the period 1988–2011, using the X1 and X2 parameters optimized during calibration. The validation results were very satisfactory, with a Nash coefficient of 74%. This high score confirms the GR2M model's ability to faithfully reproduce the observed hydrological behavior of the basin over a period independent of the calibration period. The overall application of the GR2M model therefore produced conclusive results, with parameter optimization leading to Nash values consistently above 50%, both in calibration and validation.

Analysis of the numerical results, and in particular the correlation coefficients calculated for the monthly time steps, demonstrated excellent agreement between the discharges simulated by the model and the actual observed discharges. Graphical representations of the simulated flows visually confirm this good agreement, showing a strong similarity with the flows observed across the entire basin studied. This attests to the high simulation quality of the GR2M model.

It can be concluded that extending the model's input series, using the same optimized calibration parameters for each basin, made it possible to generate reliable water inflow series from the observed precipitation data.

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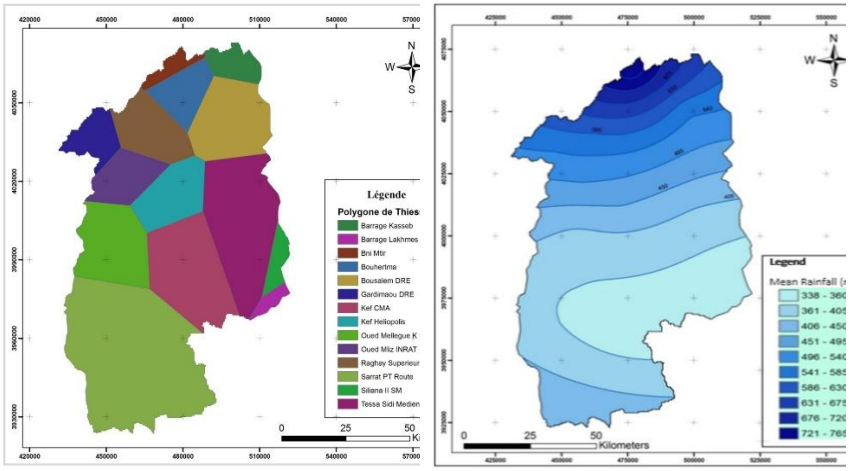

Fig. 2. Rainfall spatial interpolation by Theissen polygon and ordinary Kriging in annual scale

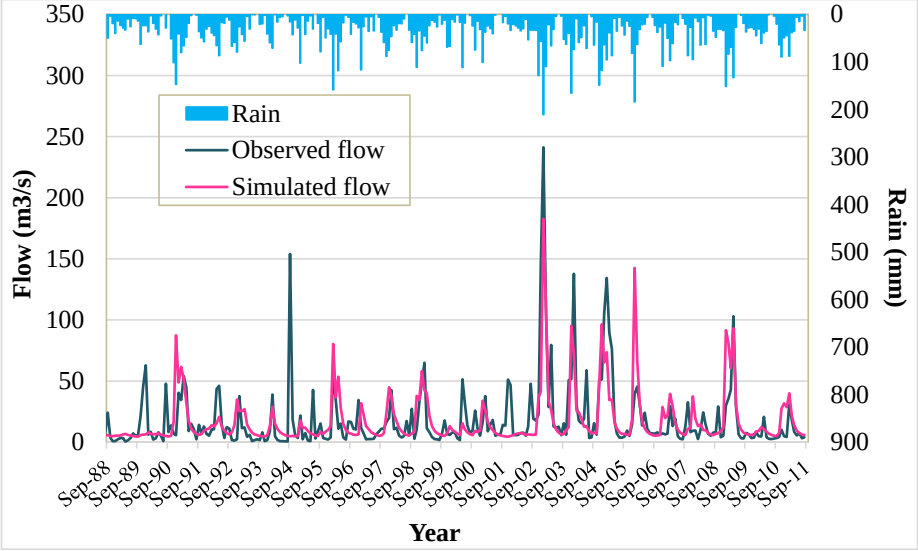

Fig 3. Rain-flow relationship of the model simulation GR2m for the period 1984/1988

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4. Discussion

Analysis of the results concerning hydrological inputs reveals considerable interannual fluctuation, directly correlated with precipitation variability and the characteristics of the Upper Medjerda Valley watershed. This variability is a striking feature of the region's hydrological regime, with notable extremes. We observed a minimum interannual input of approximately 165 million cubic meters per year (Mm^3/year) recorded during the 1988/1989 hydrological year. This low input is all the more significant given that it occurred after a relatively rainy year, with an average of 348 mm of precipitation. This apparent discrepancy between annual precipitation and inputs suggests that other factors, such as rainfall intensity, temporal distribution throughout the year, soil moisture status, or evapotranspiration conditions, play a crucial role in the transformation of precipitation into runoff. A rainy year does not necessarily guarantee high water inflows if the rainfall is not effective in generating runoff and recharging the aquifers.

In contrast, the maximum interannual inflow reached an impressive volume of 2,064 million cubic meters per year during 2002/2003, a year characterized by a high average annual rainfall of 762 mm. This record value highlights the basin's capacity to generate very large volumes of water during exceptionally wet years. It is striking to note that these periods of peak hydrological inflow coincide significantly with the major floods historically observed in the Medjerda watershed. The Bousalem region, located at the outlet of the upper valley, is particularly affected by these extreme events. These peaks highlight not only the sporadic abundance of resources, but also the challenges associated with managing natural hazards, such as flooding, which can have significant socioeconomic and environmental consequences for local populations and infrastructure.

These observations confirm the basin's sensitivity to intense rainfall events and the need for a detailed understanding of rainfall-runoff dynamics to anticipate and manage both periods of shortage and flood events. By reproducing these relationships, the GR2M model becomes a valuable tool for simulating and potentially predicting these extreme variations.

5. Conclusions

This study reaffirms that river discharges, and by extension all available water resources, constitute the direct and fundamental hydrological response of watersheds to the rainfall pulses they receive. Water dynamics in the system are intrinsically linked to the characteristics and variability of precipitation. The in-depth hydrological analysis of the Upper Medjerda Valley watershed clearly demonstrated a close relationship between water supply variability and the succession of dry and wet periods. This alternation, observed and characterized over a period of three decades, is a determining factor in the hydrological regime and resource availability. Prolonged droughts drastically reduce water supply, while rainy years can generate considerable volumes of water, sometimes in excess and posing risks. The water supply generated and modeled during this study, particularly that estimated by the GR2M model, offers promising prospects for improved and more resilient water management in the Upper Medjerda Valley

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watershed. By providing reliable supply series and powerful simulation tools, this research contributes to better water resource planning, optimized dam management, anticipation of shortages, and flood risk prevention. An increased understanding of these dynamics is essential for the development of climate change adaptation strategies and for ensuring the region's long-term water security.

Statements and declarations

Competing interests
The authors declare no competing interests.

Financial interests
The authors declare they have no financial interests.

Data availability
Data will be made available on request.

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