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HYDROCLIMATIC DYNAMICS AND WATER RESOURCE MANAGEMENT IN THE LOUKKOS BASIN (1950-2000): INSIGHTS FOR SUSTAINABLE DEVELOPMENT IN MOROCCO

SUMMARY

Morocco's sustainable water resource management is critical for its development, particularly in the water-rich Loukkos Hydraulic Basin. However, climate change projections indicate impending impacts, necessitating integrated planning. This study analyzes precipitation, temperature, and runoff data from 1950-2000 to establish comprehensive datasets, including mean areal precipitation (MAP) and mean areal temperature (MAT). Seasonal and annual regression equations linking runoff to MAP and MAT were developed, yielding historical runoff series (Qbaseline). Insights gained are pivotal for adaptive water management amidst climate change.

Keywords: Water Resources, Climate Change, MAP, MAT, Qbaseline, Multiple Regression, Management, Sustainable Development.

INTRODUCTION

Water is an essential and freely available natural resource that supports life on Earth and is also a vital factor for the economic and social development of society (Halli et al., 2023). Morocco's commitment to sustainable water resource management is paramount to its development agenda (Ouallali et al., 2024), particularly in regions like the Loukkos Hydraulic Basin, known for its abundant water resources. However, projections indicate that climate change will

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significantly impact this region, posing challenges to its water security and management strategies (IPCC, 2021).

Integrating climate change considerations into water resource planning processes is thus imperative (Badraoui & Berdai, 2011; LHBA, 2012; MEMSD, 2022; GIZ, 2013; Hahn & Fröde, 2011; WB, 2011).

This study aims to address these challenges by analyzing comprehensive datasets of precipitation, temperature, and runoff. These datasets include mean areal precipitation (MAP) and mean areal temperature (MAT), and involve the development of seasonal and annual multiple regression equations linking runoff volumes to MAP and MAT. These equations are crucial for calculating seasonal historical runoff series (Qbaseline), essential for effective water resource management and adaptation strategies in the face of climate change (LHBA, 2012).

The Loukkos Hydraulic Basin Agency's Master Plan for Water Resources (IMPWR) forms a foundational document in this context, outlining current water resource assessments, identifying challenges, proposing solutions, and setting the stage for sustainable management practices (LHBA, 2012). However, the plan did not foresee the impacts of climate change on water resources, underscoring the need for this study's integrated approach.

This introduction sets the stage for a methodological examination that systematically analyzes hydroclimatic data to enhance understanding of water resource dynamics in the Loukkos hydraulic basin. The methodology section outlines steps involving data collection, processing, and analysis, crucial for deriving meaningful insights into the impacts of climate change on water resources in Morocco's northwestern region.

The goal of research is analyze the hydroclimatic dynamics in the Loukkos Hydraulic Basin, focusing on the period from 1950 to 2000. The study aims to provide insights that are essential for sustainable water resource management in Morocco, particularly in light of projected impacts from climate change.

Key objectives of the research include: (1) Analyzing historical data on precipitation, temperature, and runoff to develop comprehensive datasets. (2) Establishing mean areal precipitation (MAP) and mean areal temperature (MAT) series. (3) Developing seasonal and annual regression equations linking runoff volumes to MAP and MAT. (4) Calculating seasonal historical runoff series (Qbaseline) to understand past hydrological trends and patterns. (5) Providing essential insights and recommendations for effective water resource management and adaptation strategies in response to climate change.

The research also aims to integrate climate change considerations into the water resource planning processes, highlighting the importance of adapting management strategies in response to projected climate impacts. By leveraging historical data and statistical analyses, the study seeks to contribute valuable knowledge to enhance sustainable development practices in the Loukkos Basin and similar regions facing similar challenges globally.

MATERIAL AND METHODS

Study area: North Morocco is vulnerable to water erosion risk (Bammou et al., 2024; Sadkaoui et al., 2024; Ouallali et al., 2024). The Loukkos hydraulic basin, located in this region, covers a total area of 13,000 km² and is known as one of the wettest regions in the country. This basin exhibits a diverse climate ranging from humid to semi-arid, contributing to a substantial renewable water potential estimated at approximately 4 billion m³/year (3,600 Mm³/year from surface water and 460 Mm³/year from groundwater, LHBA, 2012).

According to Morocco's fourth national communication to the United Nations Framework Convention on Climate Change (UNFCCC), the Loukkos basin is already vulnerable to climate-related hazards (MEMSD, 2022). Therefore, a major challenge in the coming decades will be adapting to the new context and challenges imposed by climate change (CC), while simultaneously managing these resources carefully and establishing effective and transparent mechanisms for their allocation.

The Loukkos Hydraulic Basin Agency's Master Plan for Water Resources (IMPWR), adopted in 2012, assesses the current state of water resources, evaluates water demands, identifies and prioritizes challenges to be addressed, proposes potential solutions to ensure water security in the region, and outlines the necessary means to achieve these goals (LHBA, 2012). However, this plan did not incorporate future climate change impacts on water resources.

Methodology: The methodology employed in this study follows a systematic approach aimed at comprehensively analyzing and processing hydroclimatic data to assess water resource dynamics in the Loukkos hydraulic basin. The methodological steps undertaken are outlined as follows:

Data Collection**:** Initial data collection involved gathering monthly and annual precipitation, temperature, and runoff data from relevant sources.

Preliminary Processing and Formatting: Data underwent preliminary processing to ensure uniform formatting and consistency across the time series.

Identification and Correction of Outliers: Outliers and potential data errors were identified and corrected to enhance the reliability of the dataset.

Calculation of Monthly, Seasonal, and Annual Data: Monthly, seasonal, and annual averages were calculated from the processed data to capture seasonal variations and long-term trends.

Evaluation of Series Homogeneity: The homogeneity of the data series was assessed to verify consistency and reliability throughout the study period.

Data Processing: This phase involved several key analyses:

MAP and MAT Series Development: Mean Areal Precipitation (MAP) and Mean Areal Temperature (MAT) series were developed using the Thiessen polygon method to spatially represent climate variables across the basin.

Multiple Regression Analysis: Statistical relationships between historical runoff volumes and the MAP and MAT series were established using multiple regression analysis.

Calculation of Seasonal Historical Runoff Series (Qbaseline): Historical runoff series (Qbaseline) were calculated based on the developed regression equations, providing insights into past hydrological trends and patterns.

By employing these methodological steps, this study aims to enhance understanding of hydroclimatic variability in the Loukkos hydraulic basin and support informed decision-making for sustainable water resource management in the face of climate change impacts.

Equations of the following form have been developed:

$$Q = a * MAP + b * MAT + c \quad (1)$$

Where Q is the runoff volume in Mm3, MAP is the seasonal mean spatial precipitation in mm, MAT is the seasonal mean spatial temperature in °C and c is the intercept.

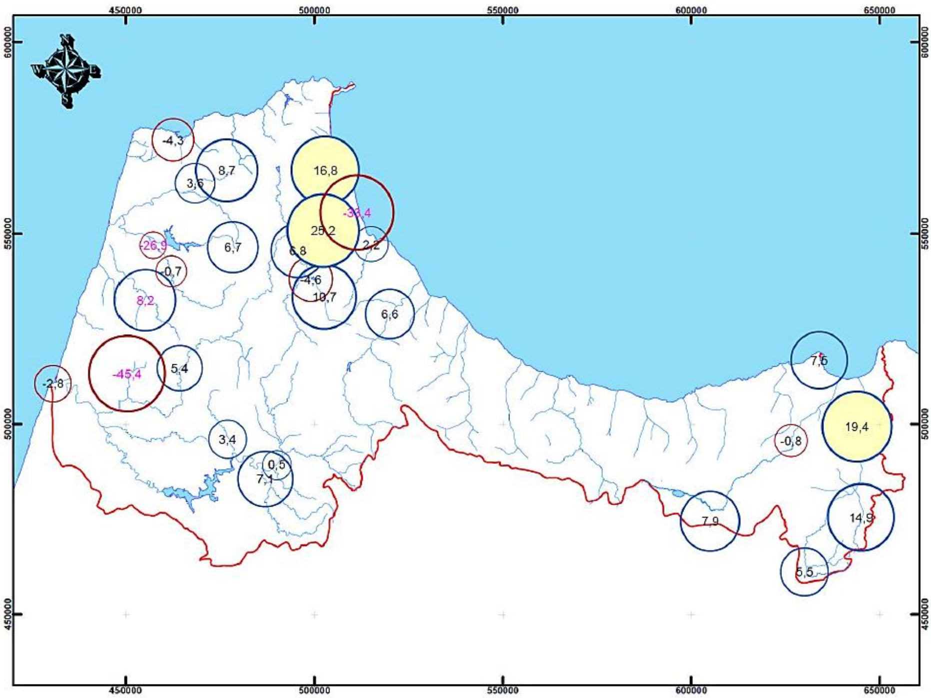

Fig. 1. Map showing observed trends in annual rainfall at LHBA.

Red circles represent a negative trend; blue circles represent a positive trend; the size of the circle represents the importance of the trend; the color of the text represents the number of years of data available (Magenta writing: Number of years <30 and Black writing: Number of years >30).

RESULTS AND DISCUSSION

For each region within the study area, specific sub-basins were selected as focal points for climate change planning, based on the availability of data. These areas are situated between the Tangier hydrological unit and the Western Mediterranean hydrological unit. The selected sub-basins were further categorized into sub-regions labelled as Q1 to Q15 and Q16 to Q20.

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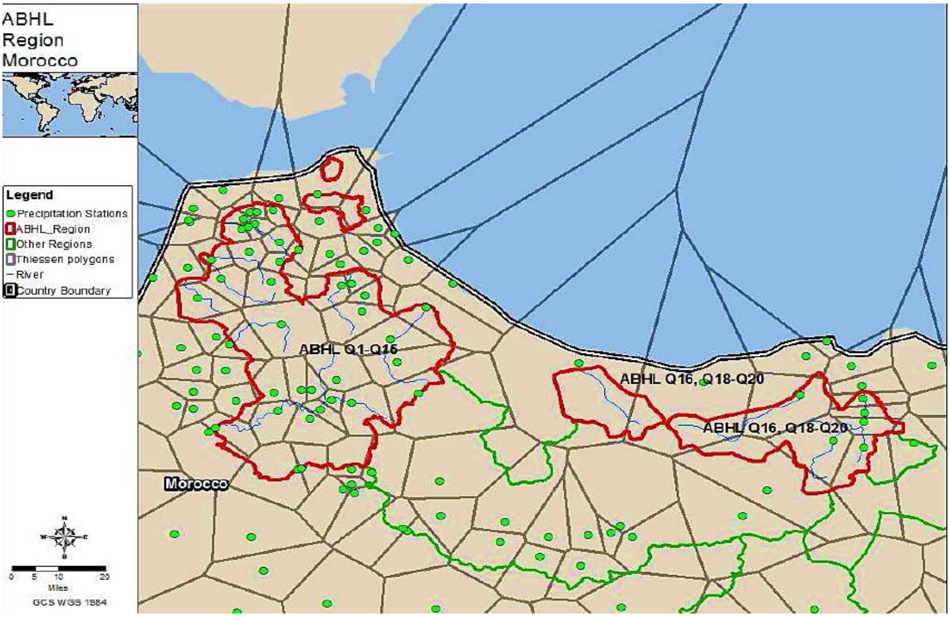

Fig. 2. Thiessen polygons of LHBA pluviometric stations for calculating the MAP series.

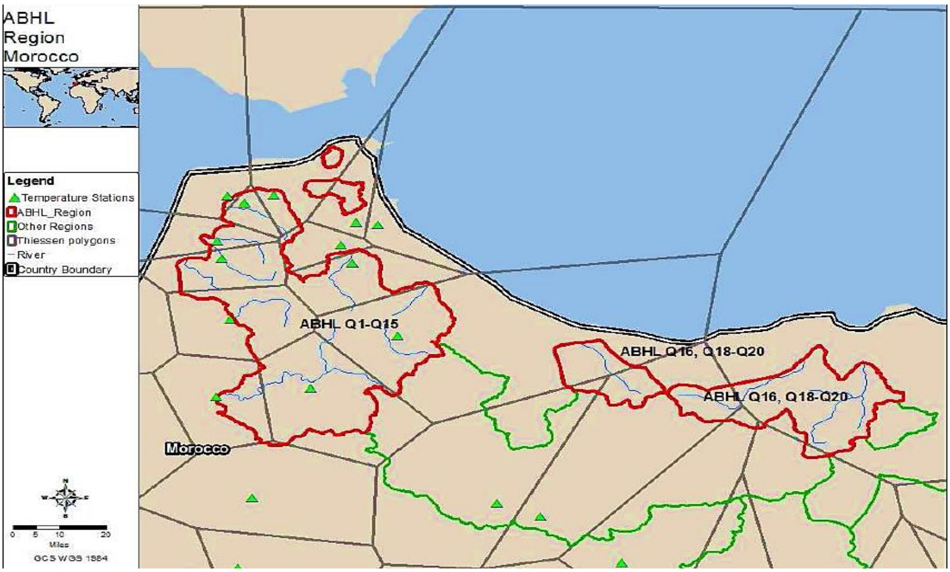

Fig. 3. Thiessen polygons of LHBA temperature stations for calculating the MAT series.

Table 1. Summary of regression equations for LHBA (Q1 - Q15).

Season	Equation	R^2
Annual	Q = -339.025 + 0.908 * MAP	0.834
1 (Dec-Feb)	Q = -124.105 + 0.939 * MAP	0.828
2 (Mar-May)	Q = 22.325 + 0.640 * MAP – 2.110 * MAT	0.627
3 (Jun-Aug)	Q = 78.728 + 0.081 * MAP – 2.868* MAT	0.133
4 (Sep-Nov)	Q = -21.586 + 0.303 * MAP	0.522

Table 2. Summary of regression equations for LHBA (Q16 – Q20).

Season	Equation	R^2
Annual	Q = 0.781 + 0.200 * MAP – 0.919 * MAT	0.660
1 (Dec-Feb)	Q = -5.261 + 0.183 * MAP	0.732
2 (Mar-May)	Q = -1.587 + 0.197 * MAP	0.703
3 (Jun-Aug)	Q = 2.632 + 0.072 * MAP	0.119
4 (Sep-Nov)	Q = -2.501 + 0.132 * MAP	0.787

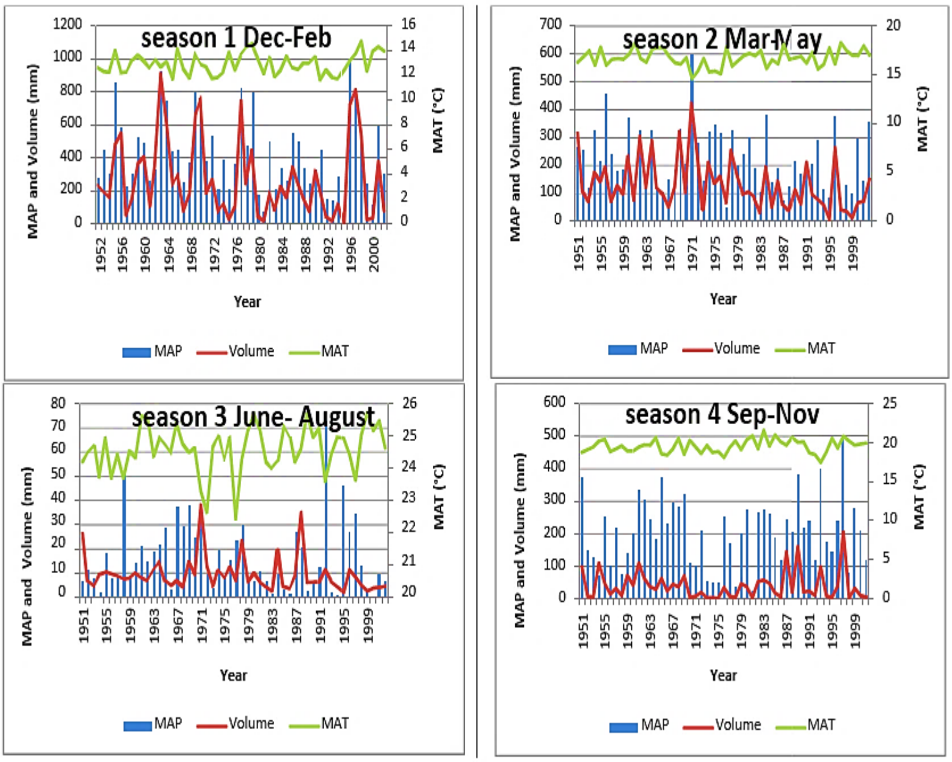

Fig. 4. Seasonal MAP, MAT and runoff for LHBA (Q1 to Q15).

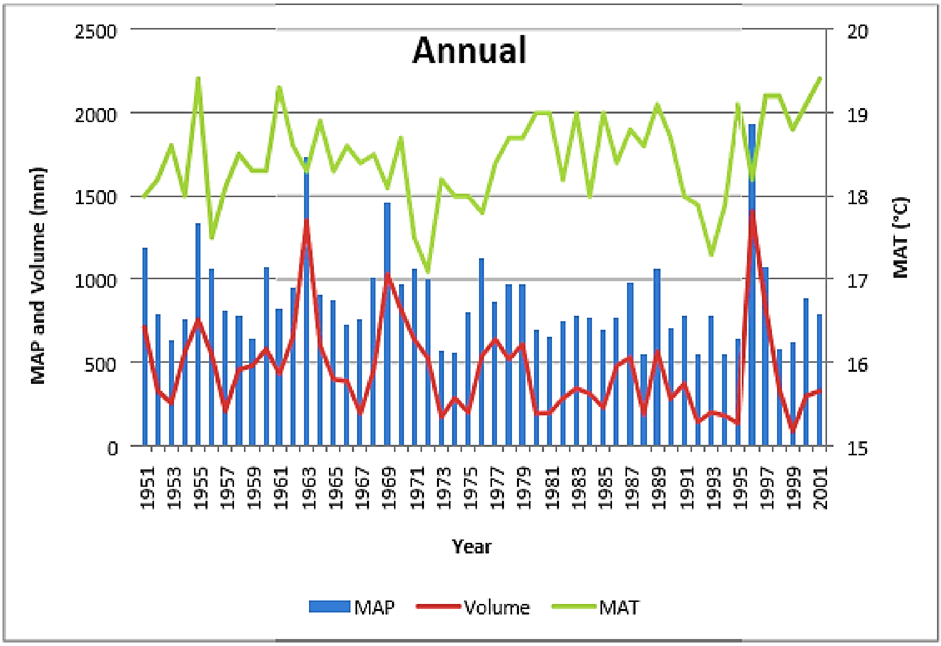

Fig. 5. Seasonal MAP, MAT and runoff for LHBA (Q16 to Q20).

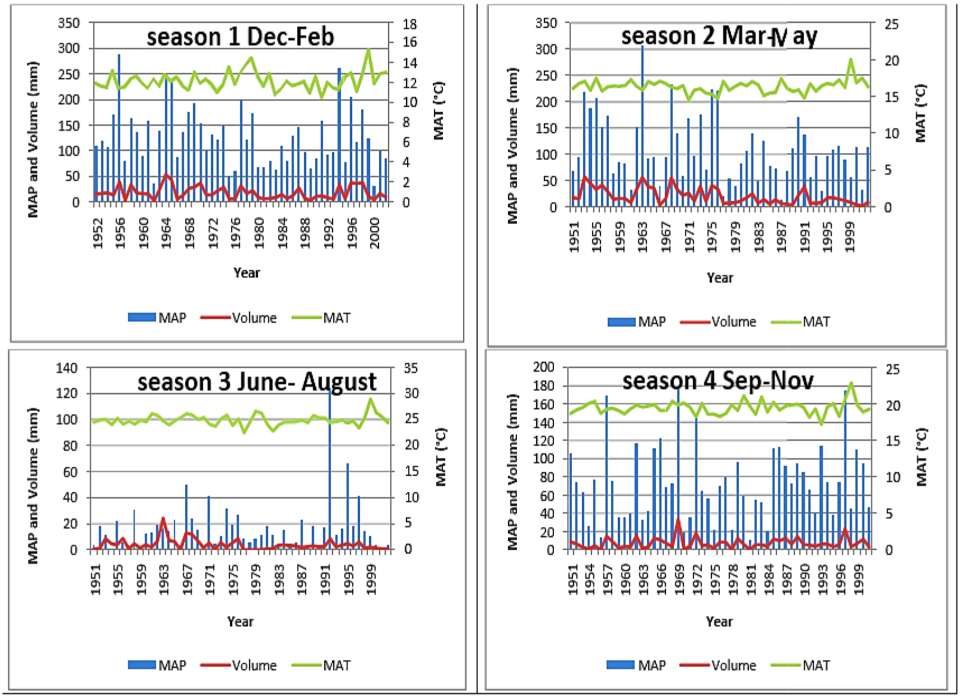

Fig. 6. Annual MAP, MAT and runoff for LHBA (Q1 to Q15).

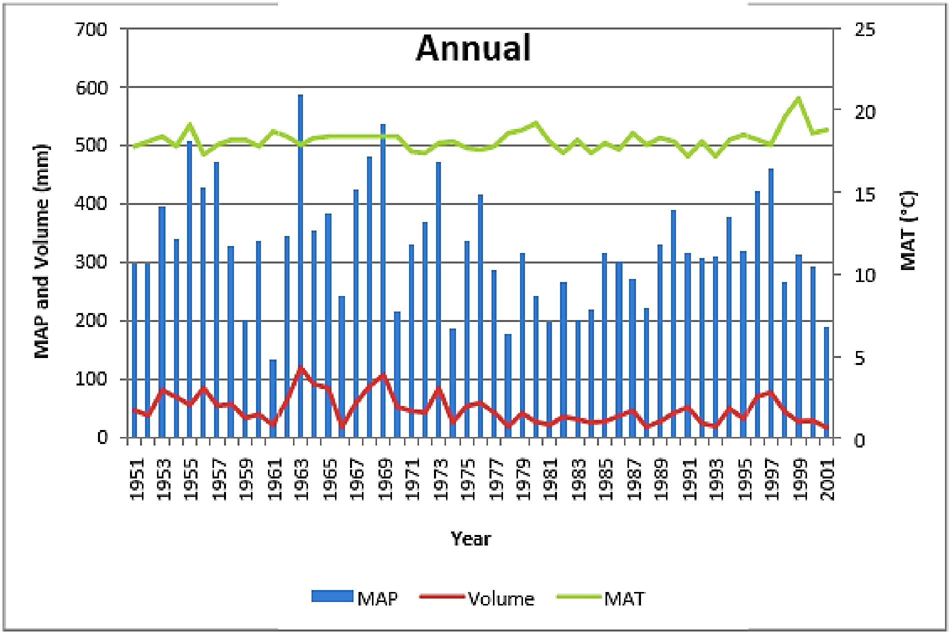

Fig. 7. Annual MAP, MAT and runoff for LHBA (Q16 to Q20).

The examination of monthly precipitation and temperature series revealed several data issues critical to understanding the hydroclimatic dynamics of the Loukkos hydraulic basin. These issues included multiple gaps and anomalies such as stations reporting consecutive years of zero precipitation across all months, specific months with recurring zero precipitation over consecutive years, discrepancies in data reported from different stations at the same location, and extended periods of missing data both in precipitation and temperature records. Additionally, outliers were identified in temperature data, further complicating the dataset's reliability for analysis.

To address these challenges, daily rainfall data from 85 LHBA stations spanning 1939 to 2012 were retrieved and analyzed. Through rigorous data validation and quality control processes, 27 stations were identified with the most complete and representative rainfall records for further detailed study. Among these, 11 rainfall stations from LHBA were selected based on their extensive data coverage from 1960 to 2011, ensuring robustness in analyzing temporal trends in cumulative annual and seasonal precipitation across the study area.

Despite efforts to secure comprehensive rainfall data, temperature data from LHBA stations were excluded from the analysis due to their limited availability and insufficient digitization. This limitation underscores the need for enhanced data management and digital infrastructure to support future hydroclimatic studies effectively.

The development of annual and seasonal Mean Areal Precipitation (MAP) and Mean Areal Temperature (MAT) series, using the Thiessen polygon method, facilitated spatial representation of climate variables across the basin. These series were pivotal in establishing statistical relationships through multiple regression analysis, linking historical runoff volumes with MAP and MAT. The regression equations provided insights into hydrological patterns and trends, crucial for assessing water resource availability and variability under changing climatic conditions.

Statistical tests conducted on the coefficients of the regression equations revealed significant relationships between runoff volumes and MAP/MAT, as indicated by high coefficients of determination (R^2) approaching 1 in several seasonal and annual models. These findings underscore the robustness of the regression models in capturing variations in runoff volumes attributable to changes in precipitation and temperature patterns.

However, challenges arose in establishing clear relationships between Mean Areal Temperature (MAT) and runoff due to MAT's inherent variability. This variability necessitates further investigation and refinement of modeling approaches to enhance predictive accuracy and reliability in future hydroclimatic assessments.

The study's findings provide a foundational understanding of hydroclimatic dynamics in the Loukkos hydraulic basin and offer critical insights into water resource management strategies amid climate change impacts. The identified data quality issues highlight the importance of continuous monitoring, data validation, and technological advancements in ensuring the reliability and accuracy of hydroclimatic datasets for informed decision-making and sustainable development planning.

Overall, this study contributes to ongoing efforts in Morocco and similar regions to strengthen resilience against climate change through integrated water resource management practices, emphasizing the need for adaptive strategies tailored to local hydroclimatic conditions.

Messages to local decision-makers in Morocco, based on the study's findings:

Highlight the pressing need to integrate climate change considerations into water resource management policies. Emphasize that the Loukkos Basin, despite its current water abundance, is vulnerable to climate hazards, necessitating proactive adaptation measures.

Stress the importance of using comprehensive and reliable hydroclimatic data for informed decision-making. The study's methodology and results provide a framework for understanding historical trends and projecting future impacts on water resources.

Advocate for sustainable practices in water management. Encourage the adoption of strategies that enhance water security, minimize vulnerabilities to climate change, and ensure equitable distribution of resources among stakeholders.

Recommend investments in infrastructure and technology that support efficient water use and management. This could include modernizing data collection systems, enhancing forecasting capabilities, and implementing adaptive measures in response to changing hydrological conditions.

Promote collaborative governance frameworks that involve local communities, government agencies, and stakeholders in decision-making processes. Emphasize the importance of transparency, accountability, and stakeholder engagement in achieving effective water resource management.

Advocate for capacity building initiatives to enhance local expertise in climate resilience and water management. Foster awareness among decision-makers about the potential impacts of climate change on water resources and the benefits of proactive adaptation.

Encourage the development of long-term planning strategies that consider climate projections and prioritize adaptive measures. Highlight the benefits of early action in mitigating risks and maximizing opportunities for sustainable development.

These messages aim to empower local decision-makers with actionable insights and recommendations derived from the study's findings, fostering a proactive approach to addressing water resource challenges in the face of climate change in Morocco.

Based on the experiences from Morocco between 1950 and 2000 regarding water resources and climate variability, several key lessons and messages can be derived for the global research society:

Morocco's experience underscores the importance of integrated water management approaches that consider both surface and groundwater resources. Research should focus on developing holistic water management strategies that balance water availability, demand, and environmental sustainability (Halli et al., 2023).

The period highlighted the vulnerability of Morocco's water resources to climate variability and change. Research efforts globally should prioritize understanding regional climate impacts on water availability and develop adaptive strategies that can be tailored to local contexts (Sreeshna et al., 2024).

Data collection and monitoring systems are critical for effective water resource management. Global research should emphasize improving data quality, accessibility, and spatial coverage to enhance predictive modeling and decision-making capabilities (Ahmad & Ureeb, 2024; Bashir et al., 2024).

Morocco's experiences underscore the importance of engaging local communities in water management practices. Research should explore participatory approaches that empower local stakeholders and integrate traditional knowledge with scientific advancements.

Advances in technology can significantly enhance water management practices. Research efforts should focus on developing and deploying innovative technologies such as remote sensing, GIS, and hydrological modeling to improve water resource assessments and monitoring (Shinde et al., 2023; Sestras et al., 2023).

Effective water governance frameworks are essential for sustainable water management. Research should investigate policy instruments, institutional arrangements, and governance structures that promote equitable access to water resources while ensuring environmental sustainability (Holland , 2011).

Enhancing technical and institutional capacity is crucial for implementing sustainable water management practices. Global research should prioritize capacity building initiatives, training programs, and educational outreach to empower water professionals and decision-makers.

Building resilience to climate change impacts requires proactive adaptation planning. Research should focus on developing robust adaptation strategies that integrate climate projections, risk assessments, and scenario planning to anticipate and mitigate water-related risks.

Given the transboundary nature of many water resources, international cooperation and diplomacy are vital. Global research should advocate for collaborative frameworks that promote dialogue, cooperation, and shared benefits in managing transboundary water bodies (Choudhary & Purushothaman, 2023).

Research should advocate for increased investment in sustainable water infrastructure, ecosystem-based approaches, and nature-based solutions that enhance water security while conserving biodiversity and ecosystem services.

All of the listed provide insights into the challenges and opportunities associated with managing water resources in the context of climate variability and change. Global research efforts should leverage these lessons to inform policy, practice, and innovation for achieving sustainable water management globally.

CONCLUSION

In conclusion, the examination of monthly precipitation and temperature series revealed significant data issues that impacted the analysis. These issues included stations with multiple consecutive years of zero precipitation across all months, such as from January to December, as well as periods with zero precipitation in specific months over consecutive years, notably continuous zeros in July. Furthermore, discrepancies were found with different stations reporting identical data despite their diverse geographical locations, and inconsistencies in data reported from the same station over time were observed. Extended periods of missing precipitation records and outliers in temperature data also posed challenges, as did prolonged periods of missing temperature records, collectively highlighting the complexities and limitations in the dataset's reliability for thorough hydroclimatic analysis.

Daily rainfall data from 85 stations operated by LHBA were retrieved spanning from 1939 to 2012. Analysis of missing data enabled the selection of 27 stations with the most complete and representative rainfall records for further study. Temporal trends in cumulative annual and seasonal precipitation across these 27 stations were analyzed to identify patterns.

Out of these, 11 rainfall stations from LHBA, with over 30 years of continuous data (1960-2011), were selected for their completeness and reliability. However, temperature data from LHBA stations were not considered due to limited availability (less than 10 years of non-digitized data).

Annual and seasonal series of Mean Areal Precipitation (MAP), Mean Areal Temperature (MAT), and runoff were plotted together to assess data quality for multiple regression analysis. These plots revealed relationships among variables and highlighted significant data shifts. MAT, being highly variable, presented challenges in establishing clear relationships with runoff.

Statistical tests were conducted to evaluate the significance of coefficients in the multiple regression equations, measured by their p-values. Regression coefficients (R^2) approaching 1 indicated a good fit of observed data to the regression model.

Efforts were made to develop complete monthly series wherever possible. In cases where base ratios were significantly wide and alternative data sources were unavailable, seasonal data filling was employed. Although base ratios ideally should be less than 2, some series exceeded this criterion (less than 10) to ensure comprehensive data coverage.

It is crucial to acknowledge that the identified inadequacies in precipitation and temperature data quality could potentially impact the outcomes of subsequent stages of this research, particularly in analyzing the impacts of climate change on water resources within the study area.

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