ASSESSING FLOOD RISK UNDER CLIMATE CHANGE BY DOWNSCALING THE MAJERDA RIVER BASIN SCALE TO A MUNICIPALITY SCALE IN BOU SALEM, TUNISIA

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ABSTRACT

Bou Salem,a small municipality located in a large transboundary river basin shared between Tunisia and Algeria, has been severely affected by the flooding of the Majadra River several times during the past few decades. This study aims to assist decision-makers in establishing a comprehensive flood management plan in Bou Salem based on a risk assessment that considers the impact of climate change. Using a new hydrological methodology, this study attempts to identify, delineate, and assess the flood risk in Bou Salem in present and future situations, considering the effects of the upstream Majerda River basin. Climate change impacts were assessed through the statistical downscaling of general circulation models over the study area using CMIP 5. All selected models consistently showed similar decreasing future annual rainfall trends. Heavy rainfall was predicted to increase in the future. Hydrological modeling with a distributed rainfall-runoff-inundation model revealed that Bou Salem was highly exposed to severe flood risk in the present situation and under the impact of climate change. Based on the research findings, mitigation measures that reduce the risk of floods in the Bou Salem municipality have been proposed at local and large basin scales. At the municipality scale, flood risk must be integrated into urban planning and urbanization must be controlled in high potential risk areas. At the large basin scale, river work improvement should be accomplished to increase river transport capacity. Moreover, the construction of new dams with integrated and optimized operation in large-scale basins could be effective as long-term flood risk reduction and climate change adaptation strategies.

Keywords: Climate change, flood, hydrological model, risk assessment, policy making

1. INTRODUCTION

The Majerda River Basin, which has its headwater in Algeria and discharges into the Mediterranean Sea, is considered the largest river basin in Tunisia, with a total area of approximately 23,000 km^2 (16,400 km^2 in Tunisia). Several large and medium–small communities which developed in the surrounding areas of the river have suffered from recurrent flood events (in 2000, 2003, 2004, 2005, 2009, 2012, and 2015) that have become more frequent in recent decades, in addition to the historical flood that occurred in March 1973 and killed more than 100 residents. Bou Salem is located in the Jendouba Prefecture in northwest Tunisia and has an area of 286.1 km^2 and total population of 36,482 residents in 2022. The town developed in the alluvial plains on both sides of the Majerdra River and, despite the existence of several upstream dams, remains as one

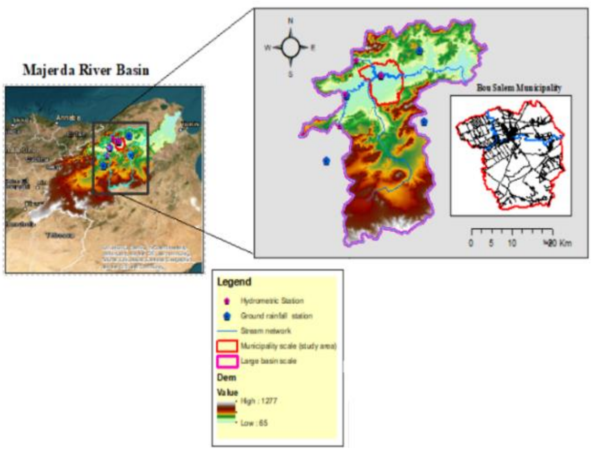

Figure 1: Study area

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of the areas most affected by Majerda flooding. This is due to the occupation of the public hydraulic domain (river domain), which is considered a very high-risk area by residents and economic and agricultural activities. Flood management has been one of the greatest challenges for socioeconomic development in Bou Salem and a major concern for local and national authorities. A comprehensive flood management plan in Bou Salem requires in-depth knowledge to understand, identify, quantify, and analyze current and predict future risks. Many studies have addressed flood issues in the Majerda River Basin using large-scale hydrological modeling and proposed classic mitigation measures. However, these previous studies did not provide detailed assessment or incorporate the impact of climate change on the flood risk at a local scale. In this context, the present study attempts to address flood issues in the town of Bou Salem through a comprehensive flood management plan based on a risk assessment that considers the impact of climate change and large basin-scale hydrological effects. Therefore, this study proposes a novel methodology for hydrological modeling that downscales a large basin scale to medium and small municipal scales using available data. The hydrological modeling in the study area was based on a distributed rainfall-runoff-inundation (RRI) model, and the climate change assessment was conducted through the statistical downscaling of general circulation models (GCM) using Coupled Model Inter-comparison Project Phase 5 (CMIP 5) under the RCP8.5 emission scenario.

2. THEORY AND METHODOLOGY

The research methodology was developed based on an end-to-end approach by linking science and technology, engineering solutions, and socioeconomic considerations such that decision-makers can make sound decisions based on cross-sectoral, multidimensional, and evidence-based approaches. Figure 2 illustrates the methodology developed in this study, with the main components of climate change, flood scenario design, hydrological model development, risk assessment, and flood mitigation measures.

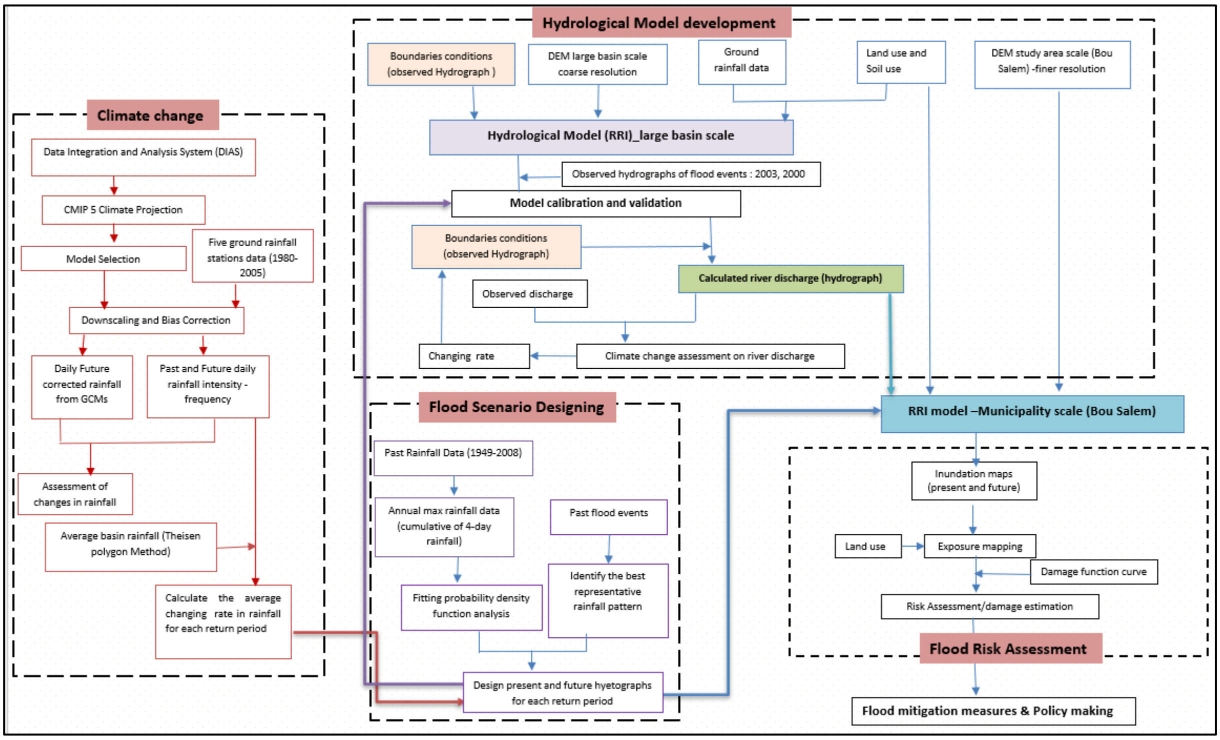

Figure 2: Research framework

i. The climate change assessment was performed using Data Integration and Analysis System (DIAS) by selecting representative GCMs of the target region through the statistical downscaling and rainfall bias correction of the selected climate models. Bias correction was processed based on five rainfall ground stations for the period of 1980–2005.

ii. A simulation of the basin-scale hydrological response to the present and future climatic conditions was conducted using a disturbed RRI model. The target area is a small town located in a large river basin to conduct hydrological simulation at the study area scale (Bou Salem), the river discharge data required for model simulation were only available at four points, three upstream river gauging stations and one at Bou Salem. Thus, we developed two types of hydrological models, the first of which uses a coarse resolution (grid size: 500 m × 500 m) to simulate the river basin-scale hydrological response. This model takes the available observed hydrographs at three river gauging stations, Jandouba, downstream Mellegue, and Bou Hertma Dam, as boundary conditions. The second hydrological model was created with finer resolution (grid size: 50 m ×50 m) to enhance the accuracy of the flood simulation at the municipality scale. It was fed boundary conditions calculated by the first model. Figure 1 shows the scales developed for the two hydrological models used in this study.

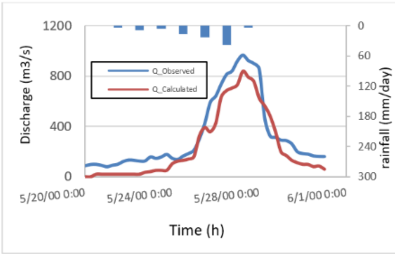

Figure 3a. RRI model validation

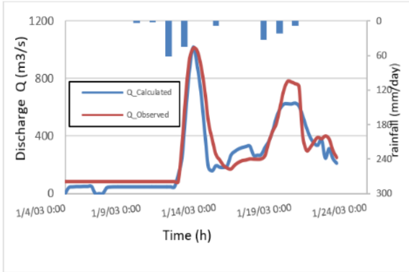

Figure 3b. RRI Model calibration

The flood events that occurred in January 2003 and May 2000 were used to calibrate and validate the developed RRI model at the basin scale. Given the quality of the available data, the results obtained after calibration and validation were satisfactory (Figures3.a and 3.b) and showed good agreement between the observed and simulated data, with NSE 0.894 for calibration and NSE 0.807 for validation.

iii. The candidate rainfall design for each flood scenario in the present and future was developed using the probability density function fitting analysis of cumulative annual maximum 4 d rainfall over a period of 60 y (Figure 4) and the rainfall pattern of the flood event in May 2000. This rainfall pattern, with a maximum rainfall intensity at the last day of the flood event, caused a more significant flood peak discharge than the rainfall patterns of other past flood events (JICA, 2013). The boundary conditions of the basin-scale model that represented the dam outflow were assumed to be the same because predicting the dam operation for each return period under present and future climate conditions was impossible. The boundary condition that represented the natural river flow at Jandouba improved in the current situation based on the hydrograph design of the flood event in May 2000. This introduced a large basin scale model with designed hyetographs for each return period derived from the probability analysis of the cumulative annual maximum of 4 d rainfall. Then, the river discharge change rate at Bou Salem station was calculated, and this change rate was applied to the Jandouba boundary condition (hydrograph).

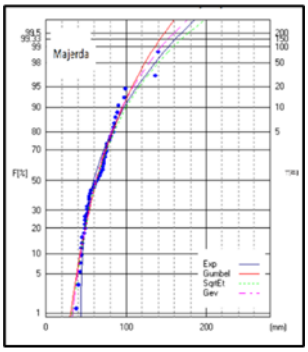

Figure 4. Rainfall probability fitting density function

iv. The impact of climate change was also incorporated into the design of the candidate rainfall and hydrographs at Jandouba for each flood scenario. The average rainfall change factor was calculated using the average frequency of the daily rainfall intensity in the basin provided by the selected climate models. The future hyetograph for each return period was obtained by adjusting the designed hyetograph under the current situation by change factor. Therefore, the future boundary conditions at Jandouba were initially assumed by simulating only the effects of future rainfall (future hyetograph) and using the same designed hydrographs in present conditions for each return period. This was then used to calculate the river discharge change rate impacted by climate change that was obtained using the simulated flood volume ratios with and without climate change. The change rate was again applied to the Jandouba boundary condition to improve the future hydrograph design.

v. The flood risk in the study area was assessed using an overlay inundation map with a GIS-based model for exposure mapping and flood damage estimation. A flood-risk matrix was developed based on the following equation:

$$\textbf{Risk} = \textbf{Hazard} \cap (\textbf{Exposure x vulnerability})$$

The hazard was quantified based on inundation depth because the study area is located in a plain where water velocity is considerably low.

3. DATA

This study used several datasets to conduct hydrological modeling and assess the impacts of climate change and risk of floods in the study area. Table 1 summarizes the data used in this study.

Table 1: Summary of data used in the study

Data	Source	Application Domain	Remarks
Daily Discharge	Direction of water resources, Tunisia	Climate change impact/hydrological modeling	1930–2019
Hydrographs	Direction of water resources, Tunisia	Hydrological modeling	Historical flood events of January 2003 and May 2000
Rainfall	Direction of water resources, Tunisia/National Meteorological Institute	Climate change/ hydrological modeling (design of candidate rainfall pattern)	1949–2009
DEM	United States Geological Survey	Hydrological modeling at the large basin scale	500 m resolution
Land use	Food and Agriculture Organization	Hydrological modeling at the large basin scale	1 km resolution
Soil use	Food and Agriculture Organization	Hydrological modeling at the large basin scale and municipality scale	
DEM	SRTM/Lidar	Hydrological modeling at the municipality scale	50 m resolution
Land use	Bou Salem municipality	Hydrological modeling at the municipality scale	
Statistical data	National Institute of Statistics of Tunisia / Field survey	Risk analysis, damage estimation	Population, housing business, curve damage function, etc.

4. RESULTS AND DISCUSSION

4.1. Climate change assessment

a) Annual rainfall

Five GCMs (CESM1 (CAM5), MIROC5, MRI-ESM1, CanESM2 and GFDL-CM3) among 44 climate models available on DIAS were selected based on their capabilities in representing the past regional climate of the target area. The comparison between the past (1980–2005) and future (2075–2100) average basin rainfall estimated by the selected GCMs after conducting a bias correction of the past rainfall (Figure 5) shows strong consistency in decreasing the estimation of annual rainfall among all models. In addition, the number of rainy days was predicted to decrease in the future, as shown in Figure 6. Therefore, according to IPCC standards, the future annual rainfall (2075–2100) will extremely likely decrease in the study area.

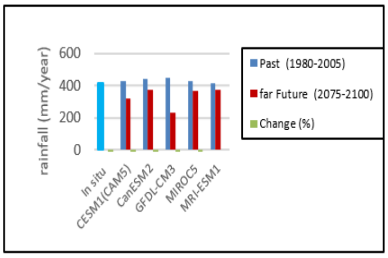

Figure 5: Estimated average rainfall in the past and future using the selected GCMs

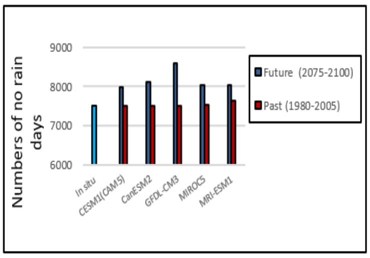

Figure 6: Estimated number of days without rain in the past and future

b) Heavy rainfall

Analyzing the impacts of climate change on heavy rainfall trends is important for the prediction of flood magnitude and frequency. The application of the innovative trend analysis method (Figure 7) in the four models shows that the intensity of rainfall over 40 mm/day will increase in the future. However, the CESM1 model predicted a decrease in the intensity of daily heavy rainfall in the study area. Therefore, climate change will likely increase the intensity of extreme rainfall, potentially causing future flooding in Bou Salem.

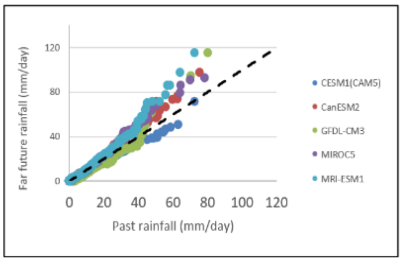

Figure 7: Innovative Trends analysis

c) Discharge

The impact of climate change on river discharge was evaluated through the simulation of a large-scale model using a designed hyetograph for each flood scenario with and without climate change. Its impacts on the river discharge at the Bou Salem River gauging station for the 10, 50, and 100 y return periods are shown in Figure 8a, 8b, and 8c, respectively. The flood volume ratio with and without climate change impacts showed an increase of +1.10, +1.22, and +1.30, for the 10, 50, and 100 y return periods, respectively.

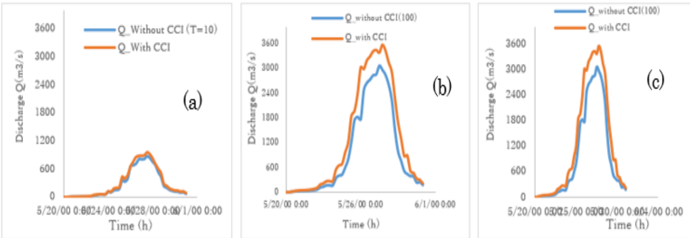

Figure 8: Hydrographs of the Majerda River at Bou Salem with and without climate change impacts for the (a) 10, (b) 50, and (c) 100 y return periods.

4.2. Flood Risk Assessment

The developed flood risk maps based on the RRI model simulation for the worse scenario case with a 100-y return period using the current climate conditions and impacts are presented in Figure 9. The figure shows that the urban area is largely exposed to flood risk, especially those near the river. This risk becomes more significant in the dense residential areas on the left side of the river. Agricultural areas are also affected by river flooding, with a large area exposed to moderate flood risk; however, agricultural areas developed along the river are more exposed to high flood risk. The future inundation map (Figure 9 c) shows that the flood extent and inundation depth will increase, thereby affecting more agricultural areas. Consequently, under the assumption of unchanged land use, the flood risk will increase in the future according to the generated future risk map (Figure 9d). This may cause a more significant socio-economic impact if an extreme flood event occurs.

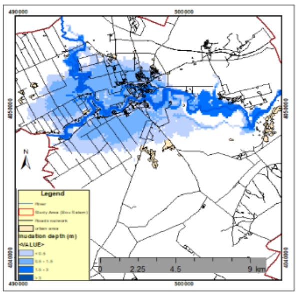

Figure 9a: Inundation map of the present situation with a return period of 100 y

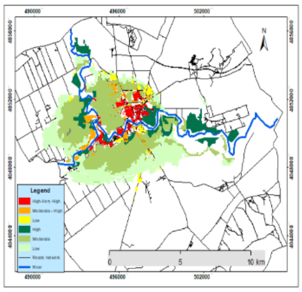

Figure 9b: Risk map of the present situation with a return period of 100 y

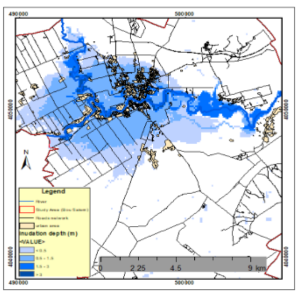

Figure 9c: Inundation map of the future situation with a return period of 100 y

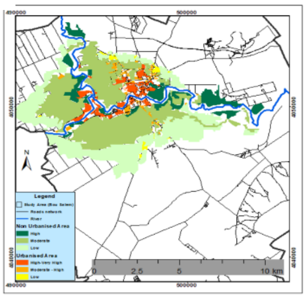

Figure 9d: Risk map of the future situation with a return period of 100 y

4.3. Damage Estimation

Flood damage in the study area under the 100-y return period scenario was estimated based on available data and damage function curves (houses and businesses) derived from field surveys. Therefore, the estimation was limited to damages in housing and small businesses. Using a flood inundation map derived from the hydrological model and damage function, we prepared a damage flood map (Figure 10) that shows that the most significant damage occurred in the city center on the left side of the river. The simulated flood caused an estimated total damage of approximately 200 million Tunisian dinars (1 USD = 3.3 TD, as of July 2023).

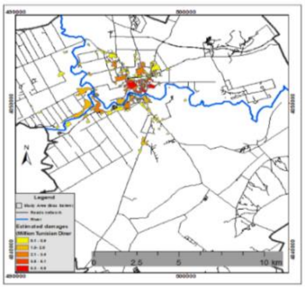

Figure 10: Estimated damages in the study area

4.4. Flood Mitigation Measures and Policy Making

The risk maps developed in this study for the current situation and under the impact of climate change show that comprehensive flood management plans must be prepared to reduce existing and potential future risks. Urban planning is an effective preventive tool to avoid increasing the risk in flood-prone areas and reducing their vulnerability as part of a global prevention policy. This planning should be based on identifying risky areas, monitoring, and even prohibiting new construction in dangerous places. In addition, it should preserve the natural storage capacity (depression) and promote natural infiltration. In high-risk areas, new construction must be prohibited, and people must be relocated to safer places. Moreover, constructing evacuation centers in safer places, conducting drills, and establishing a local evacuation plan for the town are necessary. At the basin scale, river works must be made to increase river transport capacity, the construction of new dams, and an integrated optimized dam operation could be very effective as a long-term mitigation and climate change adaptation strategy, which requires cooperation between all stakeholders at all levels, from international to national, regional, and local.

5. CONCLUSION AND RECOMMENDATIONS

The town of Bou Salem, which is located in the middle of the largest river basin in Tunisia, is exposed to a high risk of flooding from the Majerda River. This risk is predicted to increase in the future owing to climate change. The floods in this area cannot be managed with classical mitigation strategies, which focus mainly on structural measures without considering entire basin effects and involving all stakeholders at all levels, from national, regional, and local. Therefore, the new Japanese policy approach of "River Basin Disaster Resilience and Sustainability by All" may be effective in such a case, especially under the uncertainty of climate change impacts. This approach should be adopted based on short- and long-term flood reduction measures. The short terms strategy should focus on the vulnerability reduction of exiting exposure by implementing structural and non-structural measures. Meanwhile, the long-term strategy should focus on adaptive ways to alleviate climate change impacts, such as integrating dam operation to maximize water storage and mitigating the risk of water related disaster (floods and droughts). In addition, transboundary river management is important, and cooperation between Tunisia and Algeria is essential for effective flood and water resource management.

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