

# ASSESSING FLOOD RISK THROUGH INTEGRATED HAZARD AND VULNERABILITY MAPPING: THE UPPER TUNISIA MEDJERDA VALLEY CASE STUDY

## AVALIAÇÃO DO RISCO DE INUNDAÇÕES ATRAVÉS DO MAPEAMENTO INTEGRADO DE PERIGOS E VULNERABILIDADES: O CASO DO VALE DO MEDJERDA, NA ALTA TUNÍSIA

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### Abstract

This paper summarizes the hydrological modeling research results of the national CPR flood project developed by the National Center for Cartography and Remote Sensing to create a warning system for predicting and combating future floods. The watershed studied is located in northwest Tunisia, characterized by an elongated shape and bordered on one side by high reliefs that favor the convergence of flowing streams towards the Medjerdawadi. In terms of pedology, the soil texture is mainly characterized by a dominance of complex soil units and poorly evolved alluvial deposits. Following the flooding phenomenon that affected several towns around the Medjerda during the last century, our study aimed to map and delineate risk areas using hydraulic modeling methods. Flood risk analysis

### Resumo

*Este artigo resume os resultados da pesquisa de modelagem hidrológica do projeto nacional CPR flood, desenvolvido pelo Centro Nacional de Cartografia e Sensoriamento Remoto para criar um sistema de alerta para prever e combater futuras inundações. A bacia hidrográfica estudada está localizada no noroeste da Tunísia, caracterizada por uma forma alongada e delimitada em um dos lados por relevos elevados que favorecem a convergência dos cursos d'água em direção ao Medjerdawadi. Em termos de pedologia, a textura do solo é caracterizada principalmente pelo predomínio de unidades de solo complexas e depósitos aluviais pouco evoluídos. Na sequência do fenómeno de inundações que afetou várias cidades ao redor do Medjerda*



is performed using the HEC-RAS 2D hydraulic model and geographic information systems (GIS), based on several rainfall events. The exceptional floods that occurred in 2003, 2012, and 2015 brought a very large volume of water upstream of the Sidi Salem dam. Inflows from the intermediate basins on both banks, as well as the volumes released from the Mellègue and Bouhertma dams, caused spectacular flooding along the region between Ghardimaou and the Sidi Salem dam. We focused on very high-risk areas located in sectors with medium or low slopes, with varying degrees of cover. The "floodability" method is used to quantify vulnerability. Finally, risk mapping is obtained by cross-referencing the flood hazard map and the vulnerability map of the exposed issues. The aim was to determine the extent of the flooding and identify flood-prone areas. The mapping results enabled the identification of areas affected by flooding during the February 2015 flood. The flooded areas are located mainly in the town of Jendouba.

**Keywords:** Flood. Modeling. Upper Medjerda Valley. Mapping. HEC-RAS. Risk Analysis. Vulnerability Mapping.

*durante o século passado, o nosso estudo teve como objetivo mapear e delinear áreas de risco utilizando métodos de modelagem hidráulica. A análise do risco de inundações é realizada utilizando o modelo hidráulico HEC-RAS 2D e sistemas de informação geográfica (SIG), com base em vários eventos de precipitação. As inundações excepcionais que ocorreram em 2003, 2012 e 2015 trouxeram um volume muito grande de água a montante da barragem de Sidi Salem. Os afluxos das bacias intermediárias em ambas as margens, bem como os volumes libertados pelas barragens de Mellègue e Bouhertma, causaram inundações espetaculares ao longo da região entre Ghardimaou e a barragem de Sidi Salem. Focamos em áreas de risco muito alto localizadas em setores com declives médios ou baixos, com graus variados de cobertura. O método de "inundabilidade" é usado para quantificar a vulnerabilidade. Por fim, o mapeamento de risco é obtido através do cruzamento do mapa de risco de inundação com o mapa de vulnerabilidade das questões expostas. O objetivo era determinar a extensão da inundação e identificar áreas propensas a inundações. Os resultados do mapeamento permitiram a identificação das áreas afetadas pelas inundações durante a enchente de fevereiro de 2015. As áreas inundadas estão localizadas principalmente na cidade de Jendouba.*

**Palavras-chave:** Inundação. Modelagem. Vale Superior do Medjerda. Mapeamento. HEC-RAS. Análise de Risco. Mapeamento de Vulnerabilidade.

## 1 INTRODUCTION

Floods represent one of the most destructive disasters in the world. They result from the combination of several natural and anthropogenic factors, the main ones being related to climate and the edaphic characteristics of the environment [1, 2]. As humans are drawn to fertile areas near waterways, the risk of flooding accompanies this [3,4]. This problem is a serious issue in Tunisia, particularly in the upper valley of the Medjerda watershed, which has been flooded several times in recent years [5]. This region, where urban expansion has increased at an accelerated pace in recent years, is increasingly subject to intense runoff that generates flooding, causing significant damage to both urban

areas and agricultural land[6,7]. Despite all the dam construction over the past 50 years, whose primary objective is to protect the Medjerda Valley from flooding, several recent floods, especially those of January 2003 and March 2012, have shown that riverside towns and farmland have subsequently been more protected against such risks[8,9]. Faced with the risk of flooding, people have tried to protect themselves from these overflows. This study, which focuses on delineating and mapping flooding in the upper Medjerda Valley using the HEC-RAS 2D model and a geographic information system, fits into this context [10]. This study is part of the CNCT research program contract entitled "Multi-source and Multi-date Imagery for the Extent of Flood Risk in the Medjerda River Watershed." The main objective of this study is to design a hydraulic model that will make the most of all available information, in order to map some of the studied events and flood-prone areas[13]. Hydraulic modeling and GIS are particularly effective tools for monitoring flooding phenomena since they allow the affected areas to be identified, the risk to be prioritized, and risk prevention plans to be implemented [14,15, ].

## 2 PRESENTATION OF THE STUDY AREA

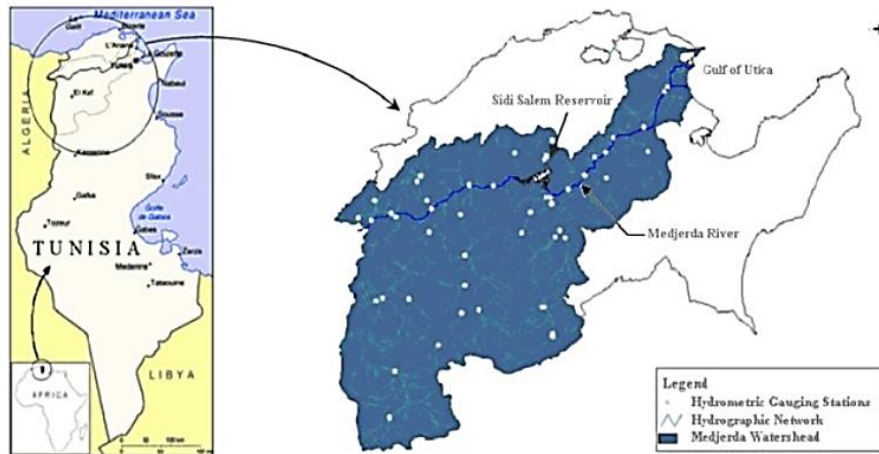
### 2.1 Geographic localisation

The study area is part of the upper Medjerda Valley. It extends from Ghardimaou to the Sidi Salem Dam. Administratively, it belongs to the governorate of Jendouba, Bèja, and Kef [17].

*The Medjerda Watershed, Tunisia's primary watershed, spans an area of approximately 23,000 km<sup>2</sup>, comprising 16,400 km<sup>2</sup> within Tunisia, and accounts for 10% of the country's total land area. The Medjerda River rises near Souk-Ahras, in the Algerian region of Constantine, and flows 484 kilometers to the Gulf of Tunis[16]( figure 1).*

#### **Figure 1**

*Location of the Medjerdawatershed [16].*

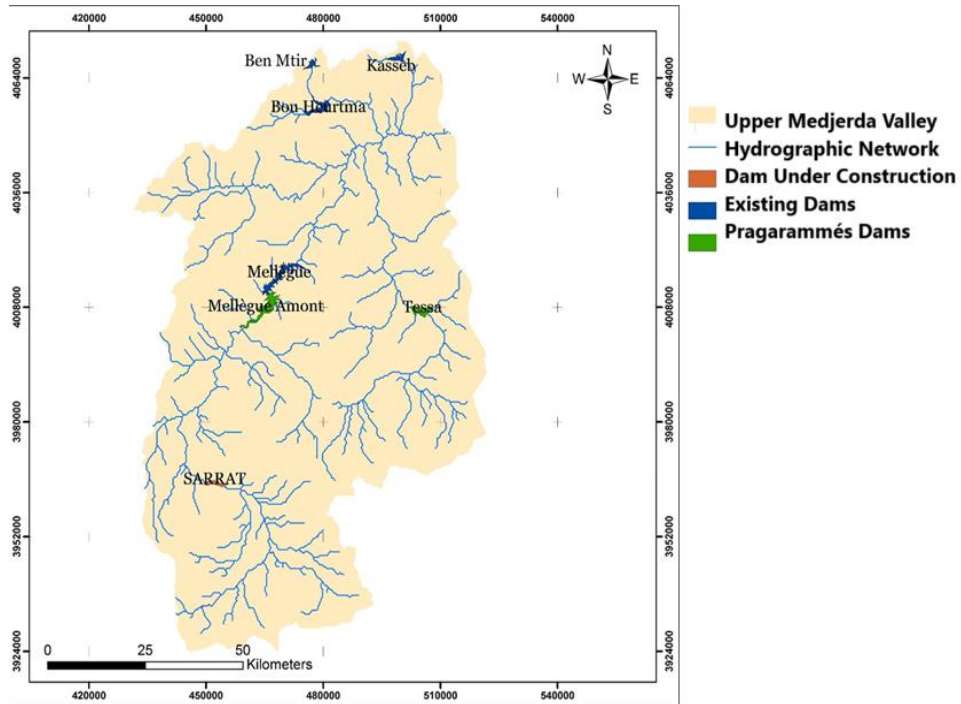


## 2.2 The hydrographic network and location of hydrometric stations

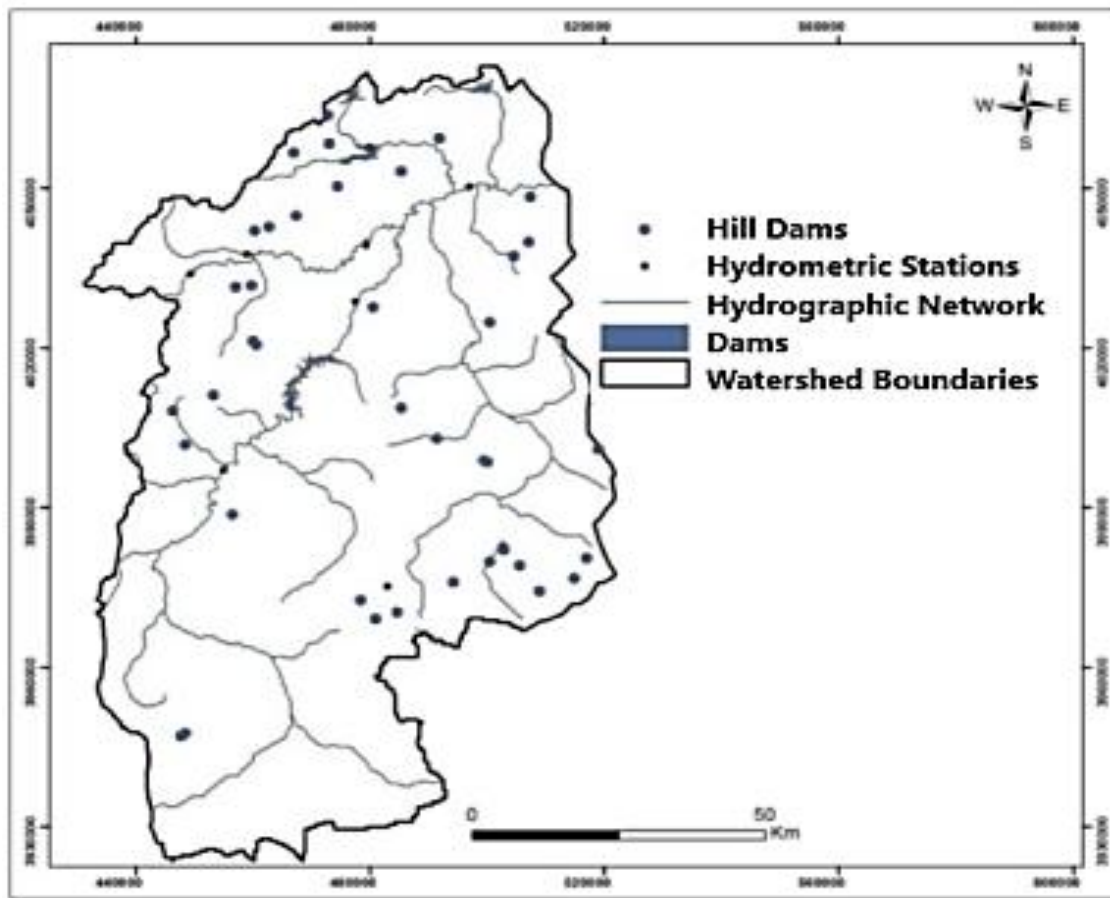
The main tributaries contributing to this watershed include several important streams distributed along both banks. On the left bank, **Oued Rarai** extends over approximately **15 km** and drains a catchment area of about **370 km<sup>2</sup>**, while **Oued Bouhertma** covers a total length of **64 km**, draining an estimated area of **390 km<sup>2</sup>**. On the right bank, the principal tributary is **Oued Mellègue**, which flows over a distance of approximately **317 km**, accompanied by **Oued Tessa**, a secondary tributary that contributes significantly to the overall hydrological network of the basin (figure n°2).

### Figure 2

*The hydrographic network of the upper valley [18]*



The upper Medjerda Valley includes several hydrometric stations. Most of them are indicated on the map below:

**Figure 3***Hydrometric stations and dams in the study area[19]*

Among these stations, we focused on those in the main valley of the Medjerda and its main tributaries. The following table presents the geographic coordinate of the stations used in this study.

**Table 1***The hydrometric stations studied*

Station Name	Longitude (decimaldegrees)	Latitude (decimaldegrees)	Altitude (m)
Ghardimaou	36.451555	8.434965	194
Rarai	36.484999	8.542290	150
Jendouba	36.501020	8.768556	150
Bou Salem	36.600707	8.966399	120
Tessa	36.278890	8.953892	330
Mellègue K13	36.120830	8.500560	327
Bou Hertma	36.676600	8.790280	242

### 3 MATERIAL AND METHOD

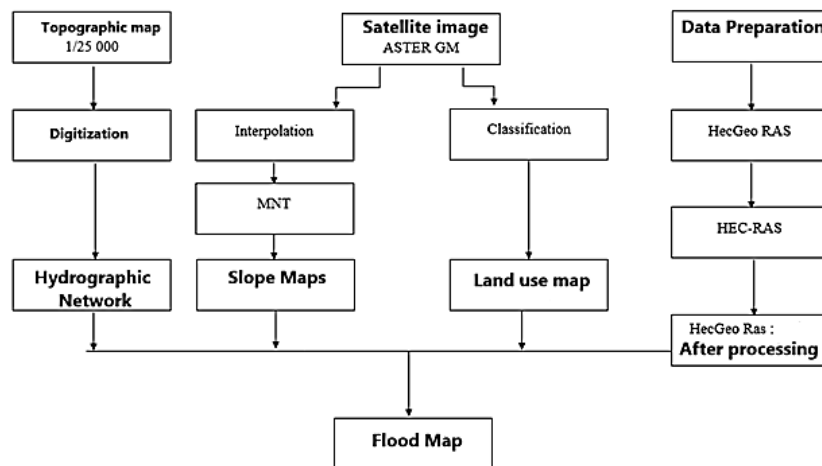
#### 3.1 Data preparation

The **HEC-RAS 5.0.3** software functions through the integration of several essential datasets that ensure accurate hydraulic and hydrological modeling. These input data can be classified into three main categories: **topographic data**, which define the physical characteristics and elevation of the terrain; **geometric data**, which describe the configuration of the river channels and floodplains, including cross-sections and structural features; and **hydraulic data**, which encompass flow conditions, boundary parameters, and other factors influencing water movement within the system[22,23,24, 26]:

The following diagram resume the methodology adopted in this work

**Figure 4**

*Schéma explicatif de la méthodologie du travail [20,21]*



#### 3.2 Topographic data

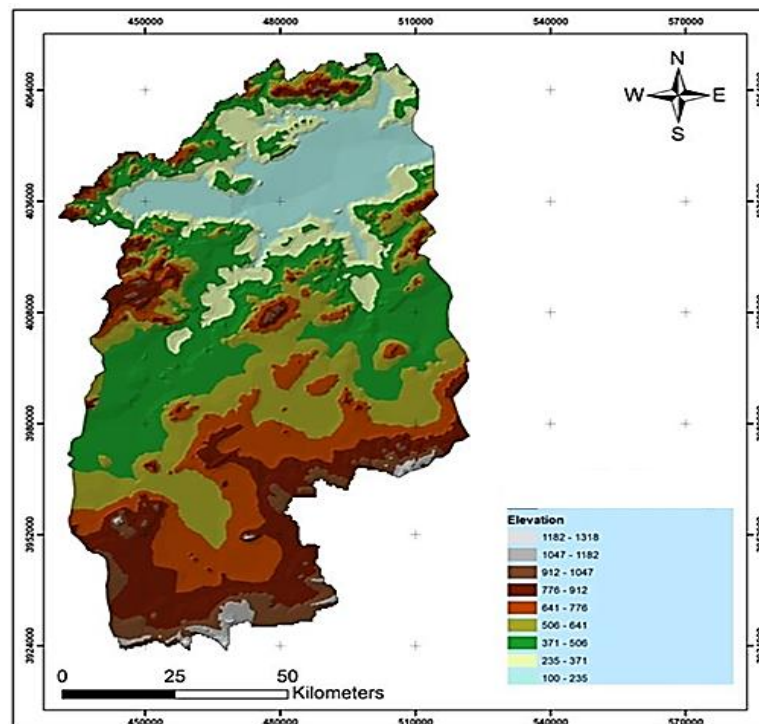
Topographic data provides a physical description of the area. For our case study, *the average slope occupies the majority of the entire watershed area. As it moves upstream, the slope becomes very steep ( $P > 25\%$ ), then decreases to very shallow ( $P < 2\%$ ). The average slope of the study area ranges from  $15\% < P < 25\%$ , hence the steep*

slope. That causes soil erosion, which becomes skeletal and consequently unprofitable even with appropriate management.

By analyzing the slope variation in all the watershed we have established Digital Terrain Model (figure 5)

**Figure 5**

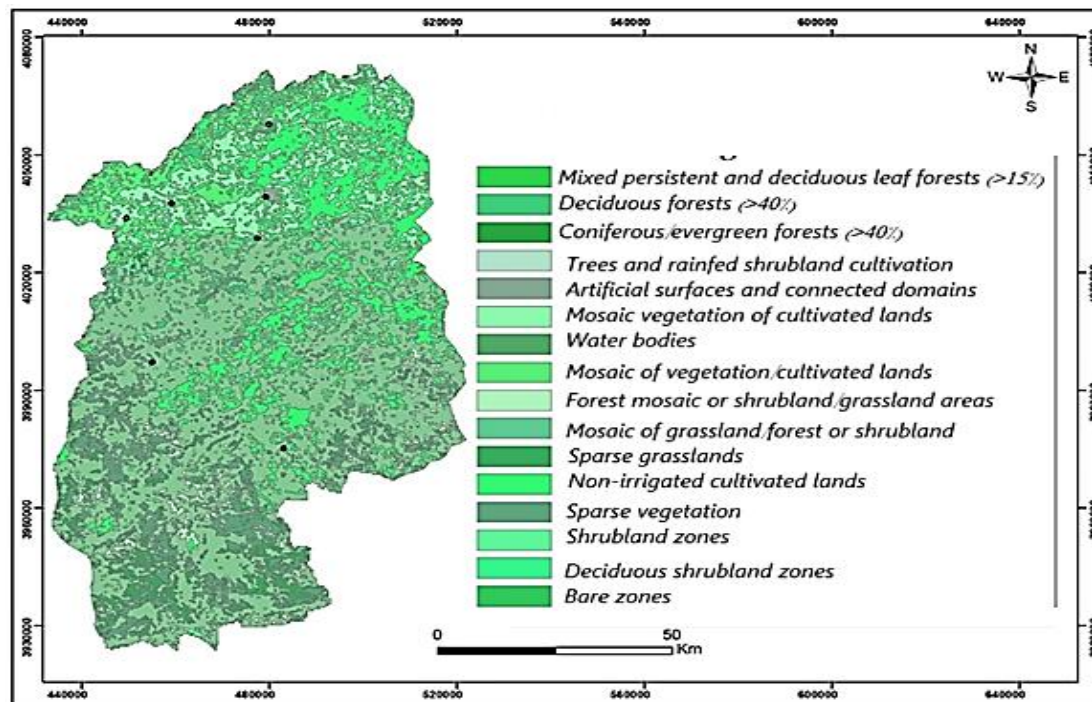
*Digital Terrain Model (Elevation in m)*



Upstream of the basin, the relief density varies between 1182 m and 1381 m, while downstream of the upper Medjerda Valley, the density varies between 100 m and 235 m.

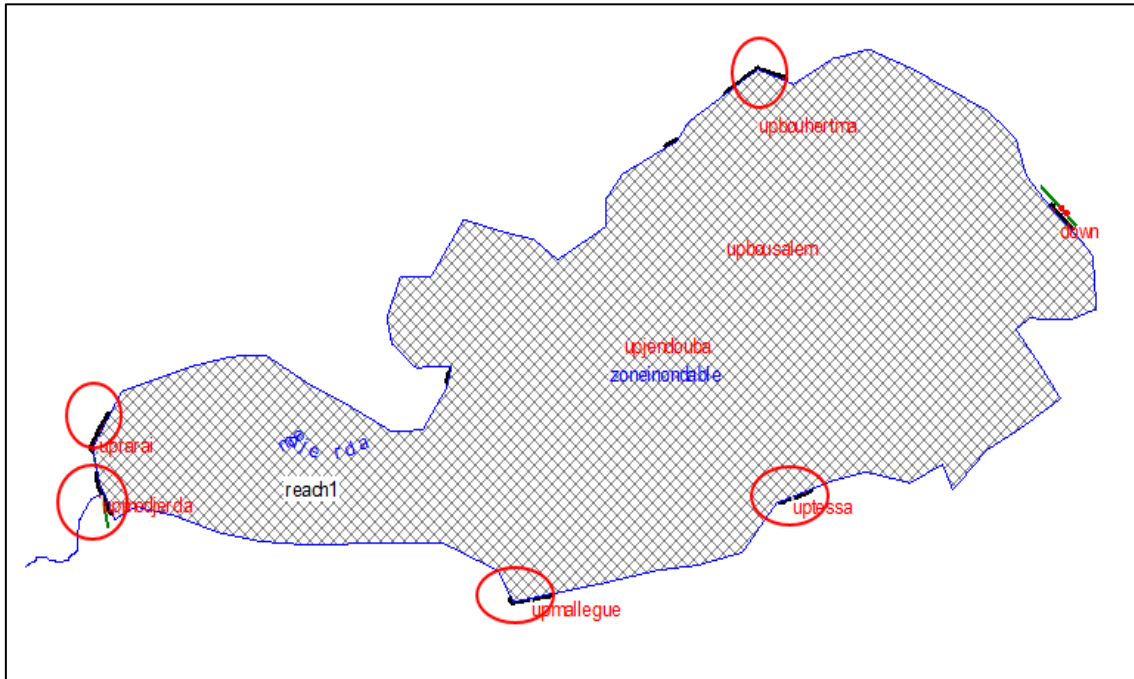
### 3.3 Land cover layer for the watershed

The establishment of the vulnerability maps and the flood risk analysis we have to represent with high accuracy the plant cover and the agricultural practices in all the watershed. The combination between the QGIS and HEC RAS 5.0.3 software allowed the elaboration of the land use map for the studied watershed (figure 7)

**Figure 6***Land use map of the upper Medjerda Valley*

We have to signal that the simulation unit is the grid cell. It is then possible to add the roughness coefficient value for each land cover class. Hence a land cover layer for the area in question can be imported in both raster and vector formats. It should be noted that the imported land cover layer must have the same projection system and spatial resolution as the flow zone grid.

Once the flow area is established, the lines that correspond to the 2D flow boundary conditions must be created. The tool used to create these lines is "SA/2D Area BC Lines" in the "Geometric Data" interface. In our case, six lines represent the boundary conditions marked by the red circles, as shown in the figure below.

**Figure 7***Definition of boundary condition lines*

### 3.4 Hydraulic data

Hydraulic data are required to perform a two-dimensional flow simulation. These data include discharges, boundary conditions, and the flow regime.

The flow regime can be steady or transient. In our case study, the propagation of the two-dimensional flood wave corresponds to a transient flow regime.

Using the HEC RAS 5.0.3 hydraulic model requires specifying upstream, downstream, and tributary boundary conditions. Boundary conditions are generally given by the water inflows at different points in the modeled river network. Using the "Unsteady Flow Data" interface, the flood hydrographs recorded at the five stations: Ghardimaou, Rarai, Mellègue k13, Tessa, and Bouheurtma were entered. In the case of the Medjerda River, the floods of January 2003 and March 2012 are reference floods. Similarly, the floods of December 2003 and February 2015 will be studied in light of the damage they caused.

### 3.5 Flood vulnerability and risk mapping

Flood vulnerability maps are created by combining geographic information systems with data on physical hazards and socioeconomic factors, using a multi-step process that includes data acquisition, hazard and vulnerability assessment, and predictive modeling. This involves gathering information on land elevation, historical floods, and rainfall, and then using models to simulate how floodwaters might spread, often overlaid with data on population density and critical infrastructure to identify where people and assets are most at risk.

Hence the vulnerability map was obtained by applying the following relationships (Ben Brahim, 2012)

$$.VulnerabilityMap = 2 \times Land\ use\ map + Slope\ map + 0.5 \times Soil\ permeability\ map + Hydrographic\ network\ map \quad (1)$$

To obtain the risk map, a combination of vulnerability maps and flood maps is used. Flood risk is expressed by Dauphiné (2002):

$$Flood\ risk = 9 \times Floodmap + 4 \times vulnerability\ map \quad (2)$$

## 4 RESULTS AND DISCUSSIONS

This section presents the modeling results in the form of profile plots and 3D views. Additionally, the impact of several estimated parameters that influence the modeling results is examined. Knowledge of the river stations is essential for understanding the hydraulic modeling results, as they relate to the location of cross-sections along the modeled channel.

Several options for viewing the calculation results are available, including various types of tabulated (synoptic tables) and graphical results that can be viewed and printed.

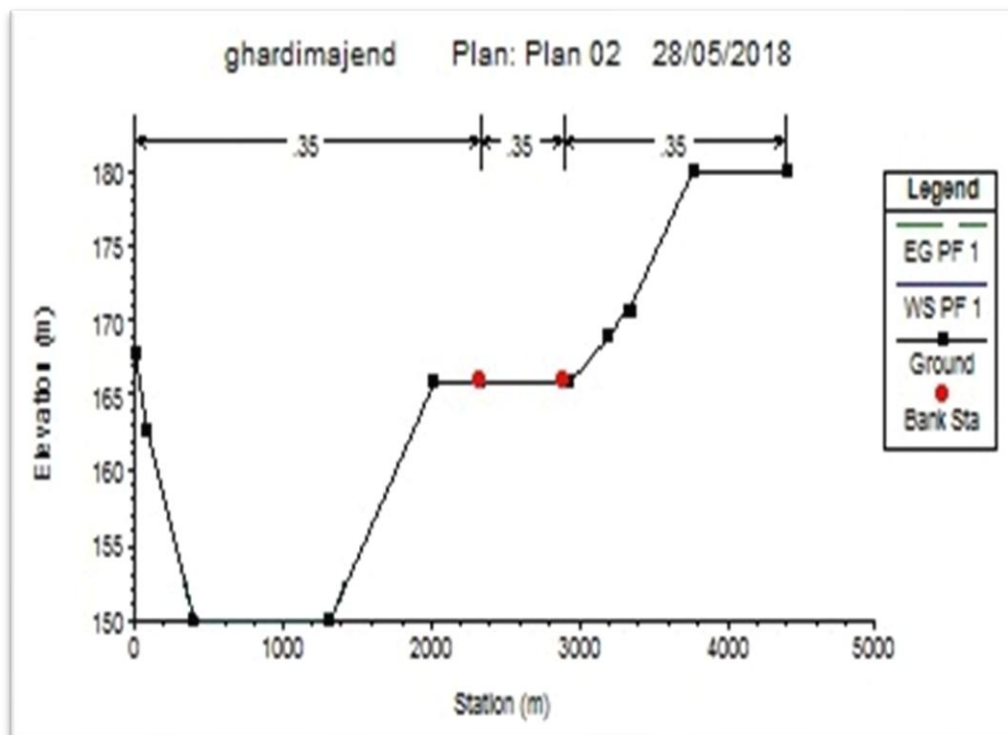
### 1D Simulation Results

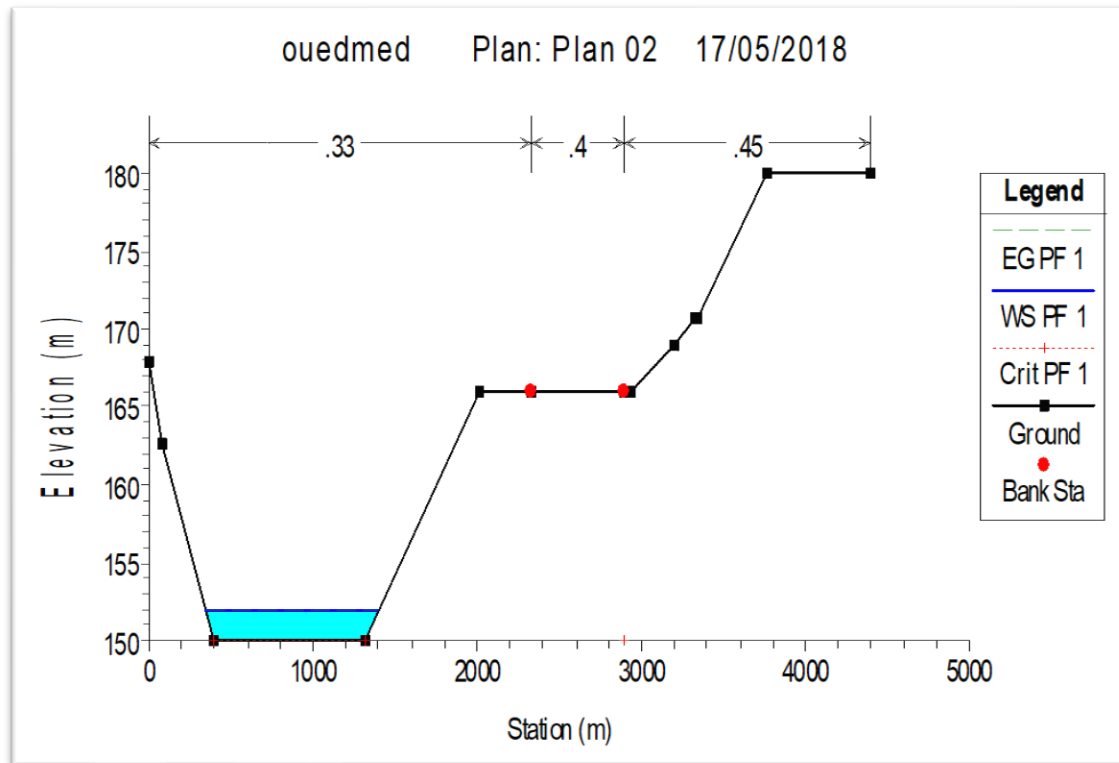
#### 4.1 Hydraulic modeling the cross-section of WadiMedjerda

Both figures 8 and 9 show the cross-section of WadiMedjerda at the Jendouba hydrometric station (arbitrary choice).

**Figure 8**

*Section before simulation*



**Figure 9***Cross-section after simulation*

Comparing the same cross-section before and after simulation gives us an estimate of the water depth in the wadi during the flood period. Similarly, the succession of cross-sections along the wadi enables us to interpret the dynamic water level during floods, as well as to gain a three-dimensional view of the water along its flow path. Comparing the different observations gives an idea of the magnitude of the flood and the volume of water it carries. In this regard, we note that the January 2003 flood was the largest, with a thickness of 28 m. The 2012 flood also carried a significant amount of water; the estimated water depth was 20 m. On the other hand, the floods of December 2003 and 2015 were less violent. The water height did not exceed 15 m. We can then deduce the longitudinal profile of the Medjerdawadi during the flood. The following figure present that profile for the period in January 2003

**Figure 10**

*Longitudinal profile of the Medjerdawadi during the flood period in January 2003*

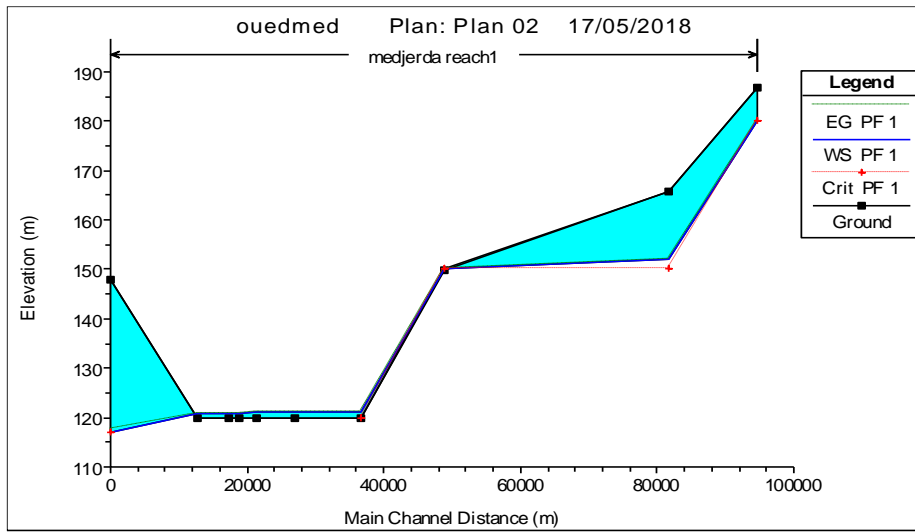


Figure 10 enables us to determine the water level in the MedjerdaWadi, which was estimated at 3 m at Ghardimaou during the January 2003 flood and reached 30 m upstream of Sidi Salem during the same period.

**Figure 11**

*Presents results of the 3D view of the MedjerdaWadi during the January flood*



It is clear that the quantity of water flowing between the two banks of the wadi as a function of the wadi's width and its slope. It provides an approximation of the wadi's overflow zones. These are the areas where the water level exceeds the level of the wadi's

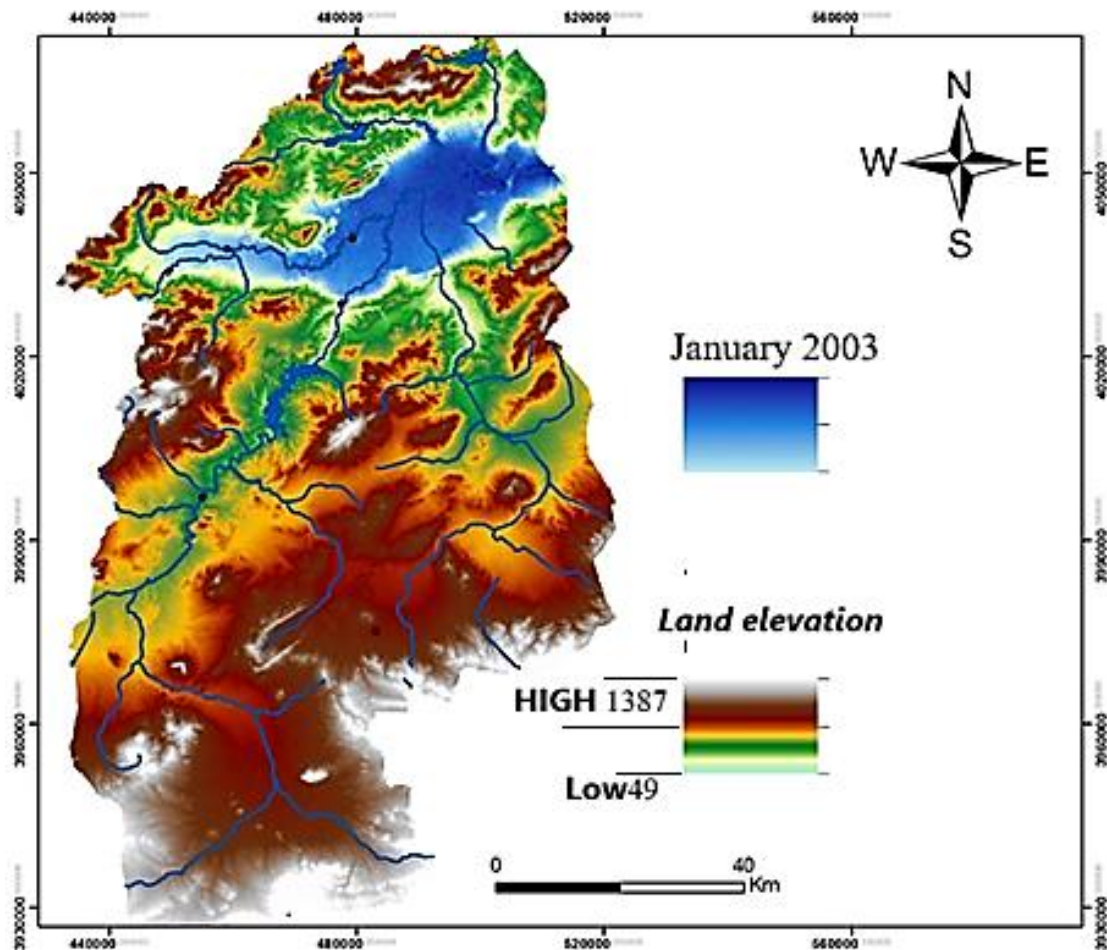
banks. The overflow zones are located mainly in the extended section between Jendouba and Bou Salem.

#### 4.2 Elaboration of flod maps by 2D simulation

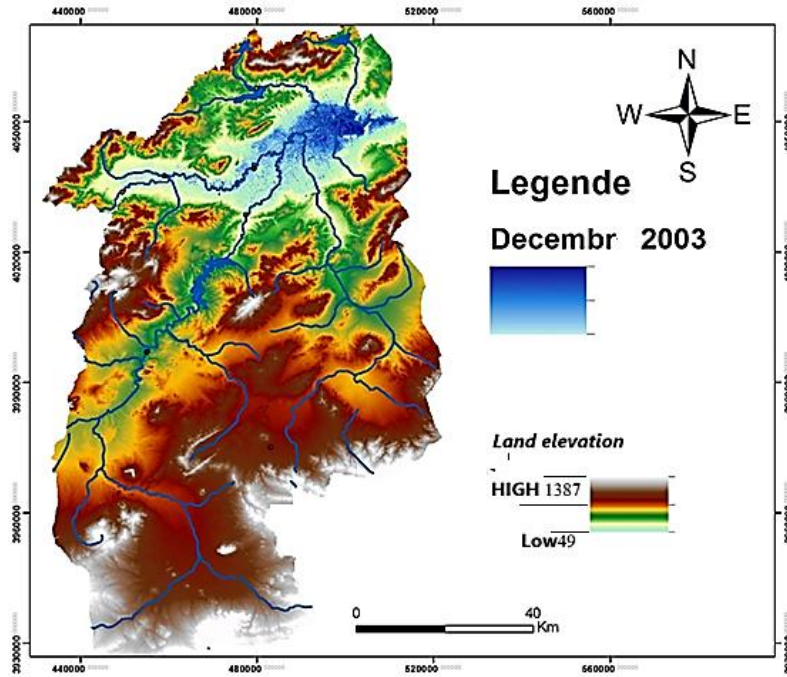
The results of the 2003, 2012, and 2015 flood simulations are presented in the figures below ( figures 12, 13, 14, 15) :

**Figure 12**

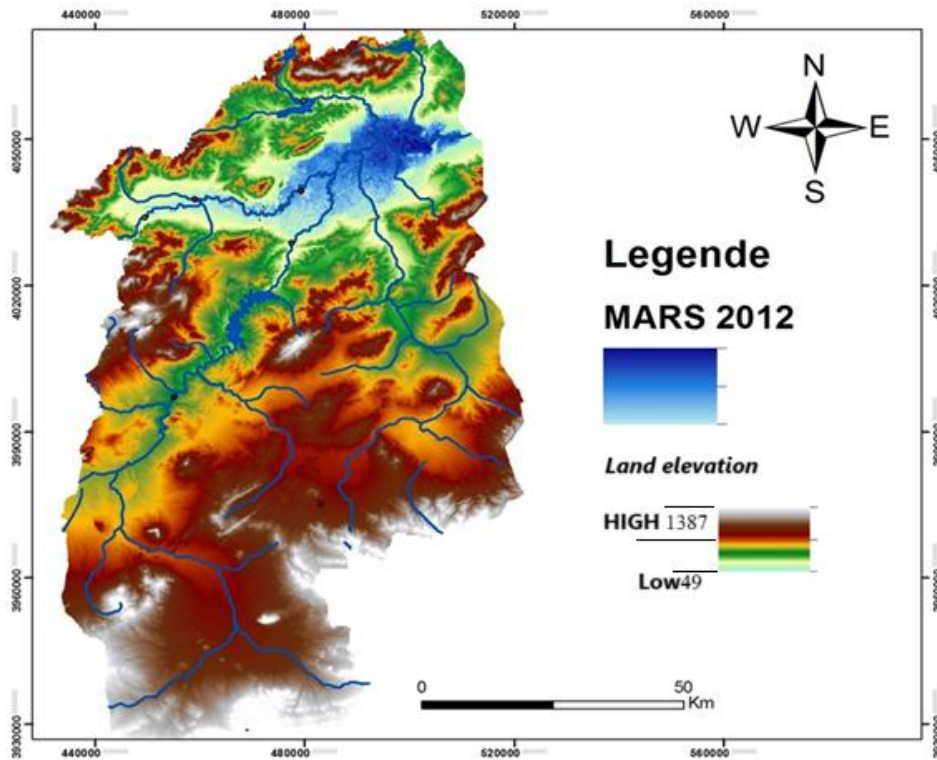
*Areas affected by the January 2003 flood*

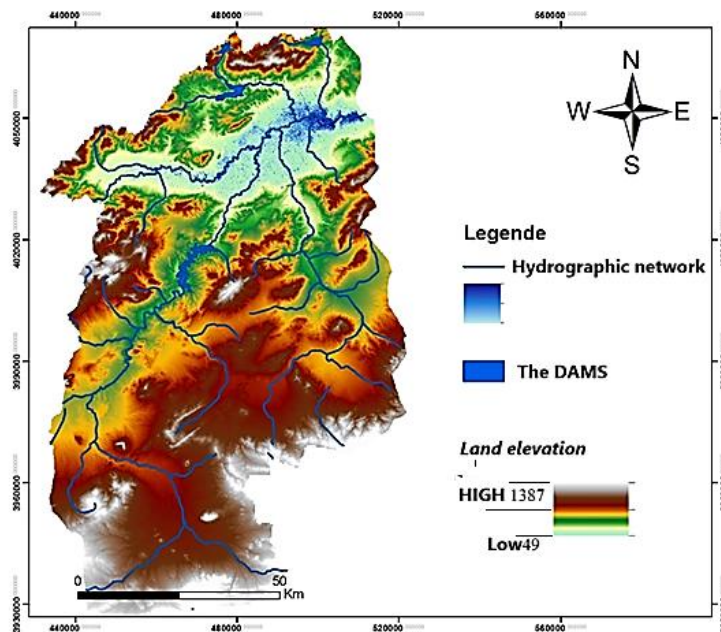


**Figure 13**  
*Areas affected by the December 2003 flood*



**Figure 14**  
*Areas affected by the 2012 flood*



**Figure 15***Areas affected by the 2015 flood*

The results obtained from the various simulations indicate that several sections overflowed during the floods of 2003, 2012, and 2015.

The areas that usually suffer from flooding are mainly located in the plains along the main watercourse of the Medjerda Wadi. These areas include the towns of Bou Salem, Ouled Arfa, Ettataouer, etc. These regions are prone to flooding and have experienced serious damage.

The floods of January 2003 and March 2012 were very violent and caused enormous damage. More than 50% of the area threatened by flooding was affected. The extent of the January 2003 flood was approximately 740 km<sup>2</sup>, while that of 2012 was 480 km<sup>2</sup>. The most affected areas are Bou Salem, Laachechiaè, and Ouled Arfa, as well as the upstream part of the Sidi Salem dam and the downstream part of the Mallégue dam near Nebeur. However, the northern part of the study area, near the Kasseb dam in Bèja, was not affected by flooding.

The floods of December 2003 and 2015 were less severe. Their extent was 370 km<sup>2</sup> and 231 km<sup>2</sup>. They mainly affected the regions of Bou Salem, Ouled Arfa, El Hanancha, Ettataouer, etc. Unlike January 2003 and March 2012, the town of Jendouba

and the downstream part of the Mallègue dam were moderately affected due to their varying altitudes.

### 4.3 Flood vulnerability mapping

The flood vulnerability map is derived from a combination of various maps: the land use map, the slope map, the hydrographic network map, and the slope map [26, 27, 28].

The vulnerability map is developed and classified into three vulnerability classes, presented in the following table 3 :

**Table 2**

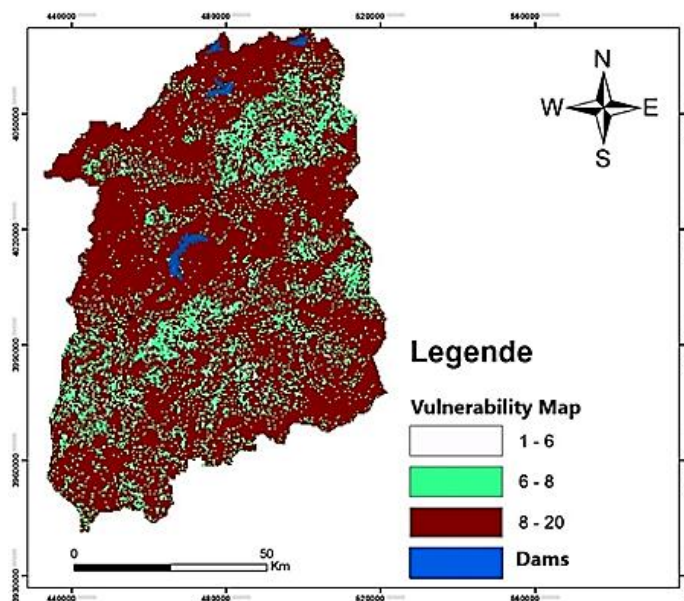
*Different flood vulnerability classes*

Range	Degrees of vulnerability
1-5	Low
5-8	Medium
8-20	High

The following figure presents our results:

**Figure 16**

*Flood Vulnerability Map*



The upper Medjerda Valley area presents morphological and geological conditions that make it vulnerable to any rainfall event, which could turn into a flood. The vulnerability map shows that more than 60% of the study area is prone to flooding. Most of this area presents a high degree of vulnerability. It essentially includes the section extending from Jendouba to Bou Salem: the regions of EzZouania, Laachechia, El Bhairia, and the towns located on the immediate banks of the rivers have the greatest vulnerability.

According to the vulnerability map, areas with high vulnerability to flooding are located in areas of low permeability and gentle slopes, and in lower elevations where the hydrographic network is more extensive (low infiltration, rapid water concentration, etc.) and vegetation cover is moderately high.

The extent of vulnerability is also linked to urbanization. Urban development increases the impermeability of land, promoting surface runoff.

Consequently, high vulnerability areas cover 60% of the territory, leading to an increase in flood risk, while low vulnerability areas cover an average of 30% of the territory. These areas concern areas with medium slopes and land use. In contrast, low vulnerability areas cover only 10% of the territory.

#### 4.4 Flood risk mapping

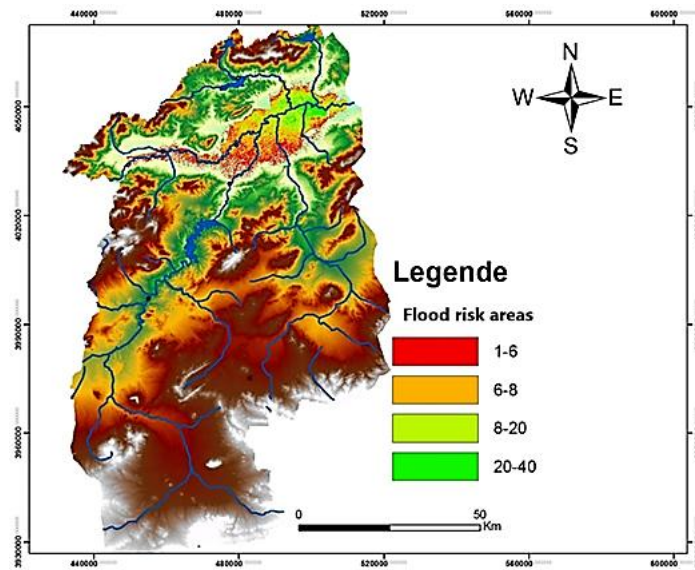
The flood risk map is classified into four vulnerability classes, presented in the following table, based on Duphinée (2002):

**Table 3**

*The different classes of flood risk*

Range	Degrees of vulnerability
1-6	Weak
6-8	Medium
8-20	Strong
8-40	Verystrong

In our study, the variability of flood hazard and its magnitude play a key role in delineating flood risk areas. In this context, the January 2003 flood is the most significant of the floods studied. The following figure presents the flood risk map established.

**Figure 17***Flood risk Map*

The map indicates four areas with varying flood risks, ranging from low to very high. The area most affected by flooding corresponds to the center of our study area, which extends mainly from Jendouba to Bou Salem. This area is particularly suited to the lowest altitudes.

These areas are sparsely urbanized and underdeveloped. They are also characterized by a more or less gentle to medium slope, which makes them more vulnerable to flooding.

We note that the flood risk is greater on the right bank than on the left bank. That is explained by the fact that the left bank is more developed than the right bank.

It is also important to note the influence of the wadi's topography on the flood risk. Indeed, the Medjerdawadi becomes very narrow in the region between Jendouba and Bou Salem. Its width does not allow it to contain the flow of running water, resulting in significant overflows. This region is also characterized by wide meanders, where low-level floodwaters overflow, creating shortcuts for water flow. The final results are presented in the form of maps. These various findings were then taken into account to establish a specific flood risk mapping methodology.

We focused on areas with very high risk, located in regions with medium or low slopes, and varying degrees of coverage. These very high-risk areas extend mainly into

the central part of the watershed. These areas present a clear danger in the event of flooding. According to the flood zone map, it is noted that the Jendouba-Bousalem section is the most exposed to flood risk due to the topography of the wadi, which narrows in this region, making it unable to contain the water flow. It should also be noted that this area is characterized by wide meanders, which favor overflows.

## 5 CONCLUSION

The Medjerda River is of vital importance in Tunisia, providing more than 80% of the water resources. The upper Medjerda Valley watershed is located in northeastern Tunisia. It belongs to the Upper Tell region of Tunisia. Its climate is semi-arid. It covers an area of approximately 9,096 km<sup>2</sup>. Calculating the watershed's geomorphological characteristics reveals that it is an elongated basin with a steep relief, and thus, its slope is very steep.

Similarly, the exceptional floods of 2003, as well as the floods that occurred in March 2012 and February 2015, brought a very large volume of water, causing spectacular flooding along the region between the Algerian border and the Sidi Salem dam.

The main objective of this project was to map flooding in the upper Medjerda Valley and identify flood risk areas. Flood risk analysis is carried out with the support of geographic information systems (GIS) and hydraulic modeling using the HEC-RAS model.

Flood mapping is summarized by developing flood maps of the studied events and a map of flood risk areas.

Flood mapping is the result of hydraulic modeling based on physical parameters selected from the study of the geometry and morphology of the watershed. The map of flood-prone areas results from the application of a parameterized method that allows for the empirical calculation of flood risk indices. These various results also allow for the quantification of the overflow of the wadi, which may have submerged an area of 740 km<sup>2</sup> in January 2003. It can also be concluded that the submersion of these areas is due to the impact of uncontrolled housing development, which narrows the wadi and reduces the flow capacity. Finally, the flood risk zone map, established by simply cross-

referencing the studied events, defines the extent and significance of flooding and provides a basis for delineating high-risk areas and implementing risk prevention plans. Using ArcGIS software, the flood risk map is generated. Based on this map, we conclude that our study area is at low to moderate risk in the city of Ghardimaou and at high risk in the cities of Jendouba and Bousalem. Many regions bordering the OuedMedjerda face flooding phenomena that manifest themselves in catastrophic ways, thus constituting a major constraint on economic and social development. These floods are among the most destructive and frequent natural disasters. Although the subject is vast, it can be considered that this work should make a useful contribution to the study of flood risk. Nevertheless, the perspectives on this topic are countless. For example, research can be extended to carry out a socio-economic study of flood risk, the use of flood reconstruction and forecasting methods, deterministic modelling, and the implementation of remote sensing and GIS tools for the environmental assessment of flood risk.

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### **Authors' Contribution**

All authors contributed equally to the development of this article.

### **Data availability**

All datasets relevant to this study's findings are fully available within the article.

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