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Hydrological Study and Hydraulic Modeling of Flood Risk in the Watershed of the Oued Lahdar (Upper Inaouene, Morocco)

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ABSTRACT

The floods of the Lahdar River cause repeated inundations and damage to road infrastructures, particularly crossing structures in the territorial center of Had Msila. Our study involved the application of various methods to estimate flood flows for different return periods along the Lahdar River. The selected flows were chosen after a comparative analysis of values calculated by the different methods used. These results served as the basis for hydraulic modeling aimed at assessing water levels to establish risk zone mapping. This step is crucial in flood risk assessment. Two main approaches were distinguished: hydrometeorological methods, based on regional parameters derived from rainfall data, and empirical methods, used in the absence or with limited data on flood flows in a given region. Hydraulic modeling was carried out using two software programs: a Geographic Information System (GIS) such as Arc-GIS, and a specific river modeling software like Hec-Ras, allowing for the numerical representation of the natural state of the territory. The results obtained serve as the foundation for all river hydraulic modeling, thereby facilitating flood prediction and hydrological risk management in floodplains. Modeling Lahdar River floods in the studied sections enables the prediction of flood risk and its impacts on constructions and infrastructure in the Had Msila Center.

Keywords: vulnerability, peak flow, flood management, hydrometeorological, Had Msila.

INTRODUCTION

Fluvial floods remain a persistent challenge, regularly affecting large populations worldwide. Despite numerous initiatives aimed at mitigating their harmful effects on inhabitants and their property, the socio-economic damages they cause continue to escalate, both in developed nations and in developing countries. Economic losses due to inland floods are considered the third most significant climate risk, after coastal flooding and food insecurity [Elalem and Pal, 2015]. This common natural phenomenon occurs consistently at the same time of year, in spring, and is characterized by a prolonged and significant rise in water levels in water bodies, often leading to river overflow. In most cases, water spills out of the riverbed. During this phenomenon, the river level can rise by several meters [Dolchinkov, 2024]. Floods are caused by the significant influx of water into the watershed due to rainfall, glacier melt, and snow. They are also attributed to climate change, which leads to an increase in the frequency and intensity of extreme weather events, such as torrential rains, responsible for sudden and devastating floods [Azidane et al., 2018]. A characteristic of winter floods is that they generally cover the same rivers or permanent river sections and occur roughly at the same time each year. Therefore, winter floods are better predicted [Kichigina, 2021]. Forecasting precipitation is important for mitigating and managing environmental flows, floods, and water demand in various regions [Alam et al., 2021]. However, due to the complexity of atmospheric processes, quantitative precipitation forecasting remains a challenge [Prusov et al., 2019]. Subsequently, an increase in the occupation of flood-prone areas is mainly due to the increased frequency or magnitude of natural hydrological phenomena [El Alaoui and Saidi, 2014].

In France, floods represent the primary natural risk, as in Morocco, where they have become an increasingly concerning issue since the 1990s [Karrouchi et al., 2016]. Over the past decades, flood damages in France have been considerable, with average annual costs estimated at 611 million euros for the period 1980–2000 [Gresillon, 2004]. This increase in damages is mainly due to urbanization and industrialization of floodplains, which have heightened the vulnerability of property and people [Torterotot, 1993].

In Morocco, floods have become increasingly concerning, especially since the 1990s, largely due to the expansion of urban and peri-urban areas on flood-prone land. These events have caused significant damage, affecting both public and private infrastructure, as well as residences and agricultural lands. Floods sometimes pollute surface water resources through the transfer of industrial waste [Chapi et al., 2017]. Unfortunately, they have also resulted in human losses, especially during flash floods, causing approximately 20,000 fatalities [Tien Bui, 2018] and affecting around 110 million people from 1995 to the present [Alfieri et al., 2017].

Flood protection has historically been at the forefront of the development of hydrology and river hydraulics [CFGB, 1994]. The economic importance of studying floods is largely explained by geographical considerations: areas with high urban concentrations are often near rivers, and the most fertile agricultural lands are typically in low-lying valleys. Other economic considerations also justify in-depth flood studies. Crossing structures represent a significant portion of the costs of road or railway infrastructure. Thus, humans have always been interested in floods, whether in their predetermination or prediction; this has resulted in a multitude of methods, some of which are outdated. However, many methods persist, and each year sees the emergence of a new method or the improvement of old ones [Mark and Marek, 2011]. However, recent extreme events have had catastrophic consequences on these infrastructures, such as the rupture of hydraulic structures (culverts, bridges, pipes), deterioration of pavements and roads, as well as the exceeding of capacities of drainage systems. Among the most devastating episodes are the Ourika Valley flood in the High Atlas watershed of Marrakech on August 17, 1995, the floods of December 2002 that affected Mohammadia, El Jadida, Taza, Tétouan, Settat, and Berrechid, the floods of 2010 in Casablanca and its surroundings, and finally those of November 2014 that struck the southern regions of Morocco [SEEE, 2009; Lemag, 2010]. The Taza region has witnessed devastating floods triggered by various wadis crossing the urban perimeter of the city. These events have occurred in recent years, notably in 2000, 2002, and 2010, resulting in human losses and significant material damages [Layan, 2014]. Floods in the Lahdar River watershed take on a much more violent and localized character compared to the major floods of the plains. It is certain that the expansion of built-up areas in flood-prone zones contributes significantly to the worsening of risks and damages observed when a flood occurs. However, despite the tragedies experienced, floods are quickly forgotten, both by residents and developers, in favor of the drought that strikes the country with much closer recurrences and much stronger economic and social consequences. The diagnosis of the existing situation has helped understand the issues posed by floods in the Lahdar River. It is evident that the problem of floods is not yet resolved. Often, several study methods are possible, and only the convergence of multiple indicators justifies some confidence in predictions. The problem of floods in the Lahdar River watershed follows this same logic. These floods, caused by violent and localized rainfall, are sudden and short-lived, but their impacts on populations and the economy are considerable. To address this risk, and in the absence of chronic rainfall-flow data, our main objective is to develop a model capable of optimally utilizing all available data. Emphasis will be placed particularly on flow estimation, which is fundamental for any hydraulic modeling to better understand hazard and vulnerability.

The Had Msila area is characterized by a very wide alluvial plain and a tributary, Rhnalla, on the left bank of the Lahdar River (Fig. 1). The study area encompasses the right part of the Oued Inaouène watershed, which is among the main tributaries of the Oued Sebou watershed. It covers an area of 611.44 km² and a perimeter of 142.21 km, accounting for 11.81% of the Inaouène basin (Fig. 1). Located between the meridians (4°15'W; 3°58'W) and parallels (34°34'N; 34°13'N), the Lahdar River watershed is bordered to the East and South by the tributaries of the Larbaâ River, to the West by the Leben River, and to the north by the upper part of the Ouergha River. The Lahdar watershed is crossed by several road networks, connecting several villages north of Taza, such as the regional road RR N 508, which passes through the Centers of Meknassa al Gharbiya, Had Msila, El Gouzate, and Taineste, as well as a series of provincial roads connecting several rural communities.

The Oued Lahdar watershed is located in the Rif mountain range, part of the Alpine chain system in the western Mediterranean, and extends eastward into the Algerian Tell, thus forming the Maghreb Mountains. The bedrock of the watershed is characterized by the predominance of soft rocks, mainly marl and marly-limestone, which promote surface water runoff during rainy phases. The topographic factor (low-altitude mountains and steep slopes) of the watershed creates highly favorable conditions for rapid surface water movement from upstream to downstream. This type of flow corresponds to a dynamics of floods with significant sediment load.

The climate prevailing in the watershed is of a Mediterranean type and belongs to the semi-arid stage. Precipitation analysis shows that the watershed is marked by significant temporal irregularity, regardless of the time scale considered, from daily to yearly, to the alternation of dry and wet periods occurring over several decades. Maximum precipitation values over 24 hours exhibit high values, even for low return times. These heavy rainfall events can occur almost every month of the year. This demonstrates that the Oued Lahdar watershed is particularly prone to generating high-volume floods over short periods. While the spatial variability of annual precipitation values

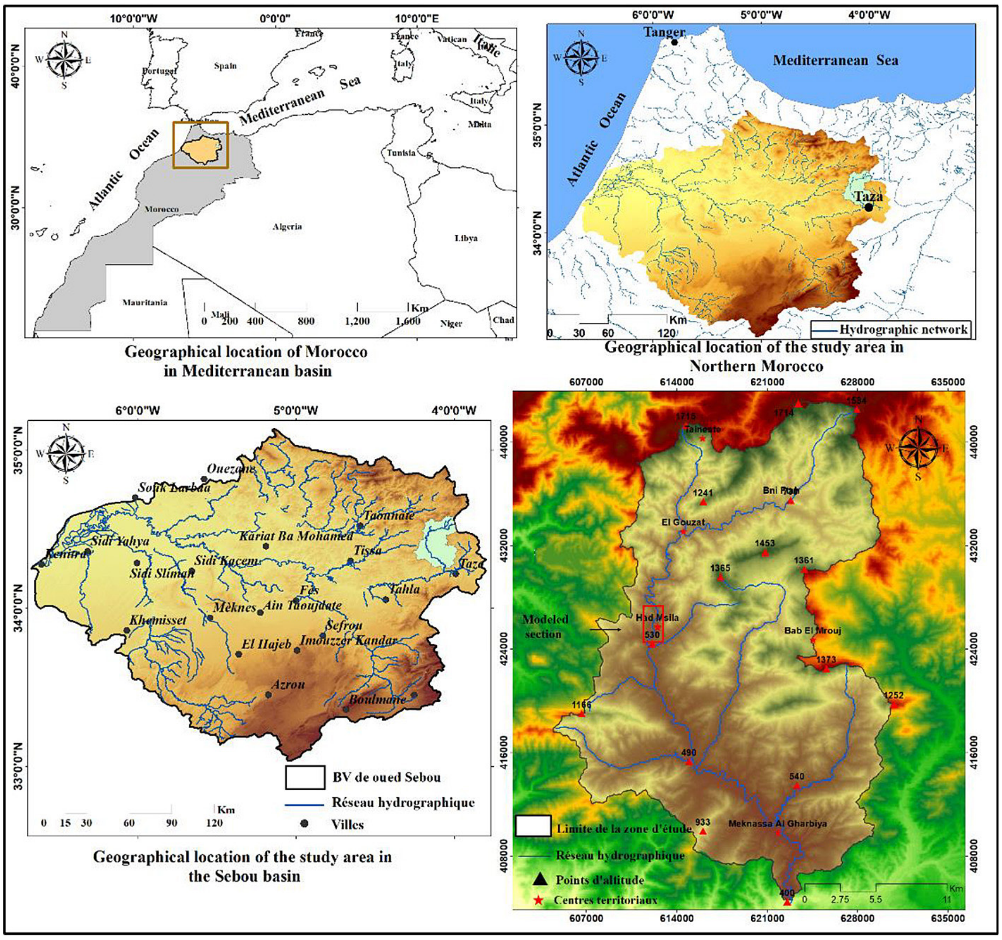

Figure 1. Location of the study area in the Oued Lahdar watershed

in the watershed is caused by orography, it does not translate into basin-scale values, as they are oriented similarly with respect to the precipitation-generating fluxes.

The spatial organization of hydrographic networks naturally has a significant effect on flow behavior, particularly on the occurrence of floods in the main hydrographic arteries. Additionally, the slope of the hydrographic network's profile plays an important role in triggering flushing processes. The vegetation cover is characterized by high density in the northern part of the watershed. Conversely, it is average to nonexistent towards the central part and the southern zone. Such a distribution confirms the impact of the orographic factor on climatic distribution in the study area.

MATERIALS AND METHODS

Hydraulic study involves assessing and integrating all fundamental parameters, such as geometry, discharge, and boundary conditions, to create a hydraulic model. This enables the calculation of water height and determines overflow areas. The hydraulic behavior of the modeled sections of the Lahdar Wadi during floods of different return periods is primarily determined by the onset of floods in the river sections and the morphology of the riverbed in the project area. The adopted flow rates are crucial for designing structures planned on the Lahdar Wadi.

Hydrological study

Determination of morphometric characteristics of sub-watersheds

The determination of characteristic parameters of sub-watersheds of the Lahdar Wadi and its drainage network forms the basis for understanding the hydrological response of each sub-watershed to the rainfall events it receives. In this regard, the digital terrain model (DTM) derived from the Shuttle Radar Topography Mission (SRTM) dataset (ESRI, 2011) was processed using the ArcHydro extension of the ArcGIS software [Jarvis et al., 2008], along with 1:25,000 topographic maps of Had Msila, Meknassa Al Gharbiya, Bni Lente, and Bab el Mrouj. The use of GIS tools enabled the precise delineation of the structural, morphological, and flow parameters of each delimited sub-watershed in a more detailed manner.

Estimation of concentration times by applying empirical formulas

The concentration time (T_c) of water on a watershed is defined as the maximum duration required for a water droplet to travel the hydrological path between a point in the watershed and the outlet of that watershed. Practically, the concentration time can be deduced from field measurements or estimated using formulas, most often empirical ones [Musy and Soutter, 1991]. In this study, we calculated the concentration time using three empirical formulas, the most used being: Giondotti's formula:

$$T_c = \frac{\left(4 \times \sqrt{Sbv}\right) + 1.5 \times L}{0.8 \times \sqrt{H}} \tag{1}$$

where: T_c – concentration time in hours, Sbv – watershed area in km^2, L – length of the thalweg in km, H – the maximum elevation difference of the watershed.

The Kirplich formula:

$$\mathrm{T_c} = 0.01947 \times \mathrm{L}^{0.77} \times \mathrm{I}^{-0.385} \tag{2}$$

where: T_c – concentration time in minutes, L – Length of the thalweg in m, I – the average slope of the thalweg in m/m.

The Turrazza formula:

$$\mathrm{T_c} = 1.662 \times \mathrm{Sbv}^{0.5} \tag{3}$$

where: T_c – concentration time in minutes, Sbv – the watershed area in hectares.

Estimation of daily mean flows using the Gradex method

The GRADEX method allows for the estimation of flow rates for rare frequencies, ranging from 0.01% to 1% [Guillot and Duband, 1967]. This method was developed by EDF (Électricité of France) since 1966. It is applicable to watersheds with areas up to 5000 km² and flood concentration times ranging from 1 hour to 4 days [Brochard et al., 2008]. This method is particularly useful for overcoming the issue of extrapolating flow rates beyond the observed range by leveraging both rainfall and hydrological data [Hamouch and Chaaouan, 2023].

- Adjustment of maximum daily rainfall using the Gumbel distribution: it can be done using various fitting distributions. The Gumbel distribution is widely used in hydrology and climatology [Makhlouf, 1994]. It is noted here that the cumulative distribution function of the Gumbel distribution is expressed as follows:

$$F(x) = exp[-exp(-\frac{x-a}{b})] \quad (4)$$

$$u = \frac{x-a}{b} \quad (5)$$

$$u = -ln[-ln(f(x)] \quad (6)$$

where: U – represents the Gumbel variable.

Therefore, the main objective is to estimate the non-exceedance probability $Fi(x)$ to be assigned to each value x. There are several formulas for estimating the cumulative distribution function $F(x)$. In the current work, we used the empirical distribution of Hazen defined as $Fi = (r–0.5)/n$, where r is the rank and n is the sample size. The data and results of applying the Gumbel distribution to the precipitation series spanning from the year 1980/1981 to 1995/1996 (17 years of recording) for the gauge station of Had Msila, and from 1993 to 2012 (20 years of recording).

- Estimation of the reference discharge (T 10 years): the Gradex method is based on the premise that beyond a certain frequency, referred to as the reference frequency T^* [Makhlouf, 1994]. This value is typically between the ten-year and twenty-year frequencies (depending on soil permeability). In our case, we will use a ten-year frequency. We will rely on the Hazan Lazarević method for this.
- Calculation of runoff depth and volume for the 10 – year frequency: determine the volume V (T = 10 years) corresponding to the reference discharge (T = 10 years) from the selected unit hydrograph for the study watersheds.

$$\text{V (T = 10ans)} = \frac{Q \times 2T_c}{2} \quad (7)$$

The reference runoff depth Lr (T = 10 years) was derived from the reference volume V (T = 10 years) by dividing the latter by the watershed area.

$$\text{Lr (T = 10ans)} = \frac{V}{S_{bv}} \quad (8)$$

- Calculation of runoff depths and mean daily discharges for different frequencies: the following formula can be used to convert 24 – hour precipitation to precipitation for the concentration time for each frequency.

$$\text{P}(Tc) = P(24) \times \left(\frac{Tc}{24}\right)^{(1-b)} \quad (9)$$

Therefore, the following equation can be used to obtain the runoff depths Lr (T/Tc) for the studied basin during the concentration time and for different return periods.

$$Gp(Tc) = Gp(24) \times \left(\frac{Tc}{24}\right)^{(1-b)} \quad (10)$$

Estimation of peak discharges Qp using the Gradex method

To calculate the peak discharge, we will multiply the results of mean daily discharges by the peak coefficient.

$$C_p = 2.5 \cdot S^{-0.07} \quad (11)$$

where: S – watershed area in km^2.

Estimation of peak discharge using various empirical formulas

The empirical method is used when there is limited or no data available on flood discharge in a watershed. It allows for estimating either peak flood discharges or frequent flow rates based on certain characteristics of the watershed, sometimes supplemented by meteorological data, particularly rainfall [Gray et al., 1972]. We focused on the most used methods in Morocco [Serhir, 2010; Ouarda et al., 2001].

- The Myer formula: Hazan-Lazarević discharges: it can calculate the flood discharge for a given urban or rural basin. The flood discharge for the design period T is calculated by the following formula:

$$Q_{max} = K \cdot A^n \quad (12)$$

where: $Q_{max}(T)$ – the flood discharge for the design period T in m^3/s, K – Myer's rating depends on the basin characteristics, A – watershed area in km^2, n – the number ranging from 0.4 to 0.8.

- Mallet-Gauthier formula:

$$Q_{max} = 2.K.log(1+\alpha H).\frac{A}{\sqrt{L}}.\sqrt{1+4.log(T)-log(A)} \quad (13)$$

where: $Q_{max}(T)$ – the maximum discharge in m^3/s, K – coefficient ranging from 0.5 for large, low-slope watersheds to 5 for small, high-slope watersheds, a – geographic coefficient ranging between 20 and 30 (in Morocco, it is taken as 20), H – the average annual rainfall module in the watershed in meters calculated from annual precipitation heights at various internal and external rainfall stations of the watershed (Thiessen polygon or arithmetic mean), A: the surface area of the watershed in km^2, L – the length of the main Talweg in km, T – the return period in years (K = 1.05, T = 10; K = 1.5, T = 20; K = 1.7, T = 50; K = 1.9, T = 100; K = 2, T = 1000).

It is noted that the values assigned to the two regional parameters (a and K) that intervene in the relationship can yield quite contrasting results if they are not fixed with a good understanding of the nature of the watershed (the topographic, climatological, and geological characteristics of the watersheds).

- Mac-Math formula: the Mac-Math formula is used to calculate the design flood discharge for a given return period. It is applied in watersheds (urban or rural) in arid to semi-arid regions, ranging in size from small to large. The regional coefficient K has high sensitivity. A detailed description and understanding of the study area are crucial. Indeed, according to the works of Ouarda et al. (2001), the difference between two consecutive values set for K will result in an absolute difference in peak discharge, which can vary between 40% and 100%.

$$Q_{max}(T) = K \cdot P(24h, T) \cdot S^{0.58} \cdot I^{0.42} \quad (14)$$

where: $Q_{max}(T)$ – the design flood discharge for the return period T in m^3/s, S – the watershed area in km^2, I – the average slope of the watershed in m/m, P (24h, T) – the maximum average 24 – hour precipitation for the return period T in mm. It is calculated by statistical adjustment based on the maximum daily precipitation values at various rainfall stations; K – a coefficient dependent on vegetation cover and topography that can be estimated from Table 1.

- Flows by Fuller 2: the description of the Fuller 2 formula is as follows:

$$Q_T = \frac{4N}{300} S^{0.8} . (1 + 2.667 \cdot S^{-0.3}) \cdot (1 + c \cdot log(T)) \quad (15)$$

where: Q_T – peak discharge for the return period T in m^3/s, T – return period in years, S – watershed area in km^2, c – regional parameter varying as tabulated, here c = 2. Region – Humid regions, value of c – 0.7–0.8; region – Arid regions, value of c – 0.8–2; Region – Saharan oueds, Value of c – 3–3.5. N is a variable tabular zone parameter, here N = 85. Region – Plains, N value – 80; region – Rugged terrain, N value – 85; region – Mountain, N value – 100.

Hydraulic study

The second phase is the simulation phase of an Oued Lahdar model. It begins by providing the basic elements necessary for the operation of the hydraulic model and identifying flood-prone areas in the basin. The identification of processes is done in four steps:

Identification of stream geometry (model construction)

Based on the selected data, the model of the watercourse under study has been developed. We primarily relied on a high-precision Digital Terrain Model (DTM) with an altitude accuracy of 1 meter, generated from the digitization of contour lines derived from large-scale topographic base (1/2000: Restitution Plan).

According to Kreis [2005], cross-sectional profiles must adhere to five main rules to ensure their representativeness:

- be perpendicular to the direction of water flow;
- must not intersect each other;
- must intersect the entire floodplain;
- must describe the longitudinal profile of the watercourse. This is not always easy to achieve in the case of meandering rivers with wide floodplains;
- must consider geomorphological modifications of both minor and major channels (widening, meandering, constrictions, bifurcations, etc.).

Table 1. Values of the regional parameter K for the Mac-Math formula [Serhir, 2010; Ouarda et al., 2001]

Values of the coefficient K	
0.11	Large watershed
0.22	Cultivated land and vacant lots in suburban areas
0.32	Undeveloped, non-rocky terrain with average slope
0.42	Undeveloped, non-rocky terrain with steep slope

The development of this geometric database was carried out using the HEC-GeoRAS tool, integrated into the ArcMap program. The created layers are imported into the HEC-RAS software to continue building this database. This step, representing the assembly of the preliminary geometric base, aims to determine all the layers constituting the framework of the valley at the level of the Had Msila centers, such as the river, banks, flow paths, etc. (Fig. 2).The geometry results of the section were integrated into the HEC-RAS software to incorporate predetermined extreme flows, in addition to physiographic parameters, notably slope and bed roughness. This allowed for the calculation of flow distribution along the river profile, facilitating a simulation of hydrological extension. The results of calculations performed with the HEC-RAS software are transferred to the ArcGIS georeferenced Geographic Information System tool for the creation of flood extent and inundation zone maps.

Identification of flow rates and boundary conditions

After introducing the geometry of the watercourse, the next step involves specifying the flow rates used to calculate the flow profiles. For this purpose, a hydraulic simulation in steady-state regime has been initiated using the five flow values obtained from the hydrological analysis, corresponding to return periods of 10, 20, 50, 100, and 1000 years.

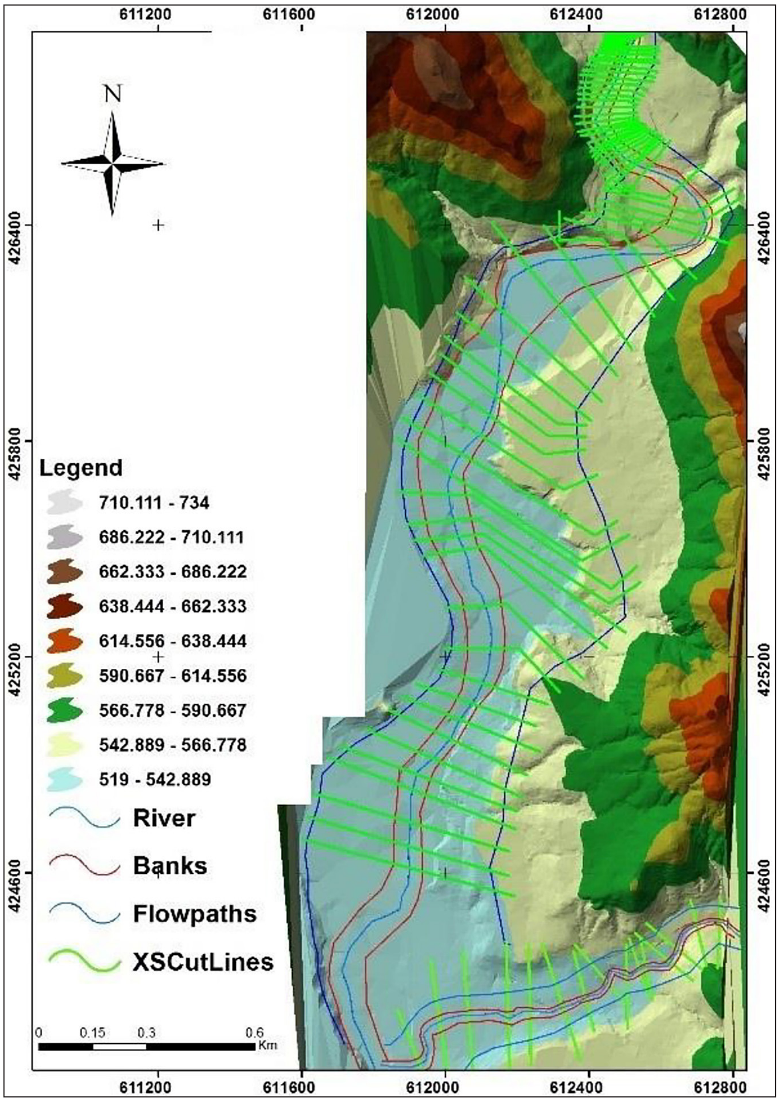

Figure 2. The geometry of the study area developed by HEC-GeoRAS within Arc-Gis, at the level of the Had Msila Center

Calibration and validation

To adjust the model, we proceeded with calibration. This involved comparing the obtained results with data from other similar regions (such as the watershed of Oued Larbaâ) and with historical event records. In this hydraulic simulation, the model was calibrated based on the flood of Oued Lahdar on 29.11.2010. In the absence of more recent data, we consider this flood to be representative of this watercourse. To achieve consistent water levels, Strickler coefficients were adjusted.

Hydraulic simulation at the modeled sectors

The simulation of the current river situation using HEC-RAS was conducted based on the results of the hydrological study. During this study, we utilized two software tools: a Geographic Information System (ArcGIS) and a river modeling software (HEC-RAS) developed by the Hydrologic Engineering Center of the US Army Corps of Engineers [USAC, 1997]. The computations of water surface profiles for gradually varied flow are based on the Bernoulli equation. Head losses are evaluated using the Manning-Strickler equation for friction terms and contraction-expansion coefficients. In the case of rapidly varied flow, HEC-RAS employs the momentum equation.

RESULTS AND DISCUSSIONS

Hydrological study

Morphometric characteristics of sub-watersheds

The watershed under investigation is delineated on the topographic map at a scale of 1:25,000 of Had Msila, Meknassa El Gharbiya, Bni Lente, and Bab El Mrouj. The following table presents the geometric characteristics of the sub-watersheds of Oued Lahdar (Table 2).

Calculation of time of concentration

The value used by the Gradex method is the maximum of the results obtained from the three formulas (Table 3).

Adjustment of daily rainfall using Gumbel distribution

The first step involves analyzing the daily rainfall data from the Had Msila station using the Gumbel distribution. The aim of this operation is to derive precipitation values associated with rare frequencies. The Gumbel distribution is employed to fit the sequence of maximum precipitations and the corresponding discharge. In this particular case, the exponential nature of the distribution is described by the slope of the

Table 2. Geometric characteristics of sub-watersheds of Oued Lahdar

Watershed	Surface (km^2)	Length of the thalweg (m)	Hmax (m)	Hmin (m)	Dmax (m)	Perimeter (km)	Shape index	Slope (m/m)
Oued lahdar (at the Had Msila level)	236.8	39310	1711	522	1189	92.5	1.70	3.02
Oued rhnalla (at the Had Msila level)	22.52	11360	1340	528	812	22.48	1.34	7.15

Table 3. Concentration time in hours by the three formulas

Watershed	Giondotti (h)	Turrazza (h)	Kirplich (h)	Tc used
Oued Lahdar (at the Had Msila level)	4.37	4.25	4.30	4.37
Oued Rhnalla (at the Had Msila level)	1.58	1.30	1.19	1.58

Table 4. Maximum daily rainfall and 24-hour rainfall by return period

Specification		Gradex	P10	P20	P50	P100	P1000
Station Had Msila	Pjmax	15.1	91.6	102.4	116.5	127.0	161.8
	P24	17.4	105.3	117.8	134.0	146.1	186.1

observed rainfall adjustment line. It is important to note that the slope of this line represents the gradient of this exponential distribution, hence the name "Gradex" method. The most frequent daily rains correspond to extreme high-intensity rainfall events that occur over a short period of time. These events occur rarely in time and space but can generate floods and significant discharge. The values indicated in the following table correspond to daily values. The estimation of rainfall over 24 hours (P24) is obtained by multiplying the value by a coefficient equal to 1.15 [ABHS, EHMHVB, 2005] (Table 4).

Estimation of the reference flow (10-year return period)

The Gradex method requires the determination of the reference flow. For this purpose, we will use the Hazan Lazarević model to calculate the flow frequency with modulation F. The selected frequency is the decennial frequency. The decennial flows for the different studied watersheds are provided in the Table 5.

Calculation of runoff depth and volume for the 10-year frequency

The data presented in the table below (Table 6) result from the application of the correlation between volume and runoff depth, while also taking into account the significant influence of the basin area on the variation of the results.

Table 5. Reference flows (Q_T10 – year m³/s) by Hazan Lazareviç method

Oueds	Q_T10 in m³/s
Oued lahdar (At the Had Msila level)	245.58
Oued rhnalla (At the Had Msila level)	50.46

Calculation of runoff depths and peak flows for different frequencies

The results vary from one watershed to another (Table 7) due to the hydrological parameters related to the geometric characteristics of the basin and the properties of its hydrological network (area, shape, slope, thalweg length, maximum elevation difference, etc.).

Estimation of peak flows Qp using the Gradex method

The results we obtained allowed us to determine flow rates for different return periods, including 10, 20, 50, 100, and 1000 years, as well as their impacts along the studied sections. In the watershed of Oued Lahdar, distinct values are observed depending on the size of the basin. These differences are explained by hydrological parameters related to the geometric characteristics of the watersheds (area, shape, slope, etc.) and properties of the hydrological networks (thalweg length, slope, elevation difference, etc.). The results of applying the Gradex method in the Oued Lahdar watershed are summarized in Table 8.

The overestimated flow rates obtained by the Gradex method are mainly attributable to the semi-arid climate, as indicated by CFGB [1994], as well as to the biophysical characteristics of the basin, such as soil permeability and vegetation cover. Thus, the Gradex method demonstrates that peak flow increases with the area of the watersheds. Indeed, the highest flow corresponds to the watershed with the largest catchment area.

Table 6. Flow rates, runoff depths, and water volumes for (T = 10 years)

Watershed	Surface (km²)	Qp (T = 10 years) in m³/s	V (T = 10 years) in mm³	Lr (T = 10 years) in mm
Oued Lahdar (At the Had Msila level)	236.8	245.58	3.79	16.05
Oued Rhnalla (At the Had Msila level)	22.52	50.46	0.29	12.74

Table 7. Average daily flows, runoff depths, and water volumes for different return periods

Watershed	Lr in mm				Water volumes in mm³				Q in m³/s			
	20 years	50 years	100 years	1000 years	20 years	50 years	100 years	1000 years	20 years	50 years	100 years	1000 years
Oued Lahdar	21.87	29.37	35.05	53.58	5.16	6.93	8.26	12.65	333.34	447.78	533.91	816.92
Oued Rhnalla	16.36	24.67	36.49	59.89	0.37	0.56	0.82	1.35	67.79	97.66	144.49	237.14

Table 8. Peak flows *Qp* estimated by the Gradex method for different return periods

Watershed	Surface in km²	Gradex method (*Q* in m³/s)				
		10 years	20 years	50 years	100 years	1000 years
O. Lahdar (At the Had Msila level)	236.8	245.58	566.68	761.22	907.65	1388.76
O. Rhnalla (At the Had Msila level)	22.52	50.46	130.22	196.30	290.41	476.64

Therefore, the flow rate of each sub-basin is proportional to its area.

Estimation of peak flows Qp using empirical formulas

Empirical methods are managed by recalculating the regional parameters involved in the four selected methods. The values assigned to these regional parameters are very important and can yield quite contrasting results if they are not set with a good understanding of the nature of the basin (climatology, geological characteristics of the basins, topographic features, etc.) [Ahattab, 2016]. This helps to better understand the magnitude of these regional parameters based on precipitation, altitude, and return period. These flow rates provide information on the hydrological importance of the Oued Lahdar watershed. The results of applying the empirical method are summarized in Table 9. Several factors must be considered when choosing the peak flow estimation method (climate, physical parameters of the watershed, data availability, data reliability, etc.). Indeed, the selected flow rates are the result of the analysis and comparison of the flows calculated by the different methods used. The flow rates calculated by empirical formulas are lower than those determined by the Gradex method.

Hydrological study

According to the flood flow rate of each river, the water level and the distribution of flow rates in each elemental section vary. This depends on the flow rates in each of the rivers and their flow capacities. Inputting geometric data concerning the profiles of cross sections and the flow rates of projects with different return periods, as well as boundary conditions into the Hec-RAS software, allowed for calculations to be performed and results to be extracted such as the simulated profile view of the section, water level for each return period on the profiles, a three-dimensional view of the water level in the study section, descriptive tables, and the rating curve.

Analysis of flow velocities

The obtained results represent the variation in water flow velocity for each return period as a function of distance from the outlet on the left bank, center, and right bank of the river (Fig. 3). According to the graphs, a similar trend is observed for all water levels: an alternation of velocity variation, sometimes increasing and sometimes decreasing as one moves from upstream to downstream of the section. It is noted that the velocity increases at the outlet, which is attributable to the variation in the topography of the studied area. Additionally, it is observed that the velocity varies between the right and left sides of the section, being higher on the left side along the river. In general, flow velocity directly influences the extent of erosion and the volume of sediment transported by floodwaters. For instance, in the case of the Had Msila section, according to Figure 3, the speed varies with distance due to changes in the terrain's topography. Downstream and from the outlet, the speed is moderately low, measuring 3.5 m/s at a distance of 3280 m, and begins to increase, reaching 6.2 m/s at 3600 m, attributed to a steep incline. In the river's center, the velocity is higher than on the right and left banks. Overall, flow velocity directly impacts flow rate and floodwater intensity.

Table 9. Peak flows Qp obtained and selected by various empirical methods for different return periods

Watershed	Q1000 in m³/s (Hazan Lazareviç)	*Q* in m³/s (Mallet-Gauthier)					*Q* in m³/s (Mac-Math)					*Q* in m³/s (Fuller 2)				
		100 years	20 years	50 years	100 years	1000 years	10 years	20 years	50 years	100 years	1000 years	10 years	20 years	50 years	100 years	1000 years
O. Lahdar	628.30	149.26	257.52	347.25	429.04	571.92	213.62	277.71	359.90	424.50	602.08	245.58	278.44	321.87	354.73	463.88
O. Rhnalla	93.87	31.12	51.28	66.97	81.54	105.93	78.32	101.81	131.95	155.63	220.74	50.46	57.21	66.14	72.89	95.32

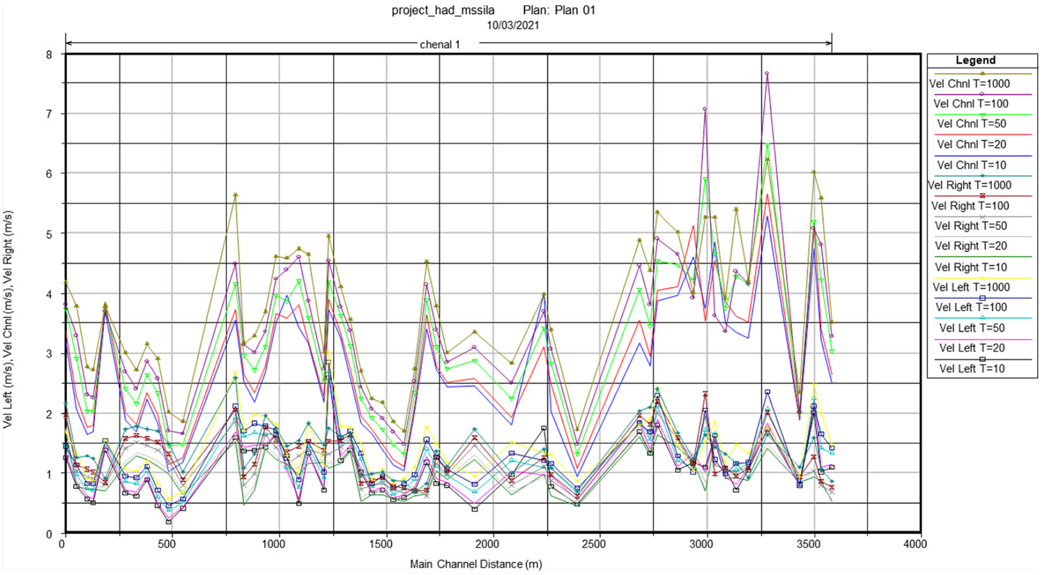

Figure 3. Flow velocity as a function of distance for each return period (Had Msila section)

Water line

The water line represents a profile view of the study section with the water level and surface of the river, as well as the water level for each return period. Hec-RAS program uses these profiles to illustrate the levels reached by floodwaters of different return periods. The results of this simulation allow for comparison of the heights of each section during different floods. Figure 4 shows the longitudinal profile of the watercourse in the existing situation. It is observed that the water level for the 10-year flood varies from 1 m to 3 m over a distance of 0 to 100 m. From this distance (x = 100 m), there is a progressive increase in water height for return periods of 50 to 100 years. Thus, this area is potentially flood prone. In this analysis, the disparities between the levels corresponding to different return frequencies are clearly discernible. Flood characteristics are influenced by variations in topography.

Restoration of the rating curve

The Hec-RAS software has provided a representation of water level variation (in meters) as a function of discharge (m^3/s) in the modeled sections at the Had Msila Center. The rating curve describes the experimental relationship between water levels and corresponding stream

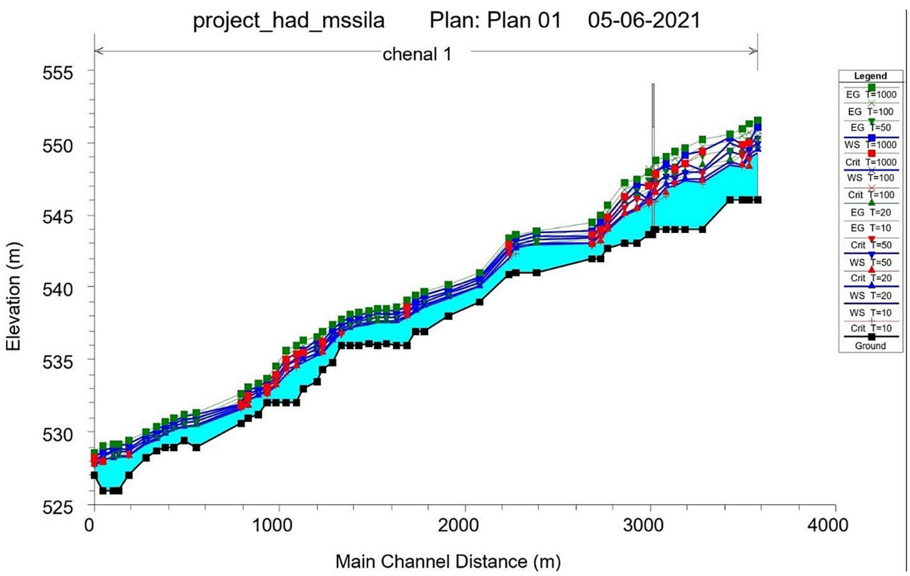

Figure 4. Water level of the modeled section of the Oued Lahdar (Had Msila section)

discharges. The curve connecting the experimental points typically appears linear for high and moderate water levels; in the absence of a mathematically faithful equation representing it, the relationship is utilized graphically. Each studied section has its own characteristics. The rating curves highlight the difference between the seven sections on one hand, and between the upstream and downstream of the same section on the other hand. For example, a discharge of 245.58 m^3/s corresponds to 5 meters upstream and 2 meters downstream of the Oued Lahdar section, which represents the main watercourse of the Had Msila Center (Fig. 5).

The causes of instability in the water level-discharge relationship are manifold, including changes in the riverbed, the growth of aquatic vegetation, the presence of ice upstream or downstream of the measuring section, as well as the accumulation of debris.

Identification of sites at risk from project floods

The objective of this modeling is to simulate floods of the Oued Lahdar for various return periods and then generate maps of water levels and flow velocities for the reference flood. These parameters will be subsequently used to establish flood zone maps. The hydraulic simulation of decennial, twenty-year, fifty-year, centennial, and millennial floods in the current state of the Oued requires a thorough analysis of the natural terrain topography and flow characteristics in the study area. While the results obtained for different floods are promising, implementing these numerical models remains a complex task, necessitating the collection of extensive spatio-temporal data from various sources and disciplines. Additionally, the study area poses several modeling constraints due to the numerous meanders in the hydrographic network. Displaying the results by cross-sectional profile provides the opportunity to obtain detailed insights at each selected point along the river's course:

- decadal flood – the discharge of the decadal flood of the Oued Lahdar at the Had Msila Center is 245.58 m^3/s. This discharge flows through the alluvial plain at the centers. The wetted section, whose width varies depending on the morphological characteristics of the river plain, would not cause major flooding. Only some overflows are observed at the level of the R 508 road, connecting the Had Msila Center and the Taineste Center, which is already within the flood zone on the left bank of the Oued. The maximum overflow height relative to the upper edge of the left bank is 3 m (Figure 6a). However, the road overlooks the channel by 2 to 2.5 m (Figure 6b). Indeed, this road is regularly threatened by floods, leading to the disruption of road traffic and the isolation of residents of the Msila Center and neighboring hamlets (Figure 6b). This road section is even more vulnerable due to the highly active undercutting of the concave bank, which exacerbates the frequency of inundations. At the Had Msila Center, the flooding event on 04.11.2011 illustrates this decadal flood occurrence. Indeed, the Msila station recorded 85 mm of daily rainfall, a value equivalent to a 10-year return period.
- twenty-year flood – on November 29.2010, the Lahdar watershed experienced significant rainfall exceeding 110 mm, which lasted for several days, resulting in floods of the Oued Lahdar. These floods persisted for several days and caused damage. The precipitation

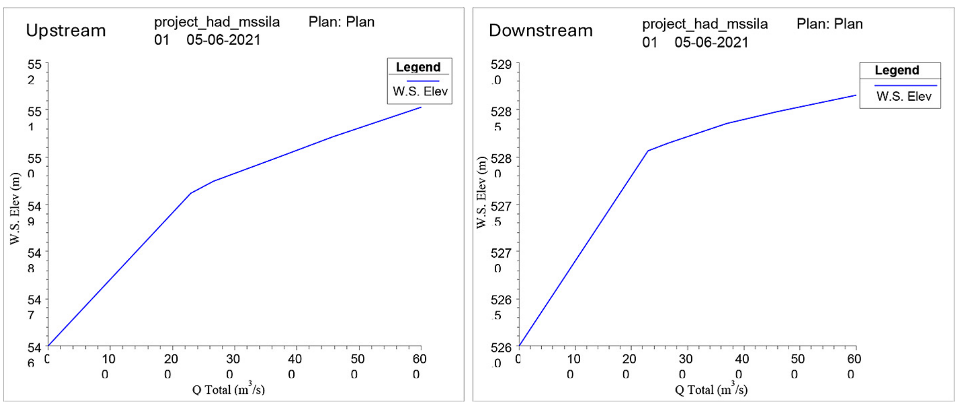

Figure 5. Rating curves obtained from Hec-RAS for Oued Lahdar (Had Msila section)

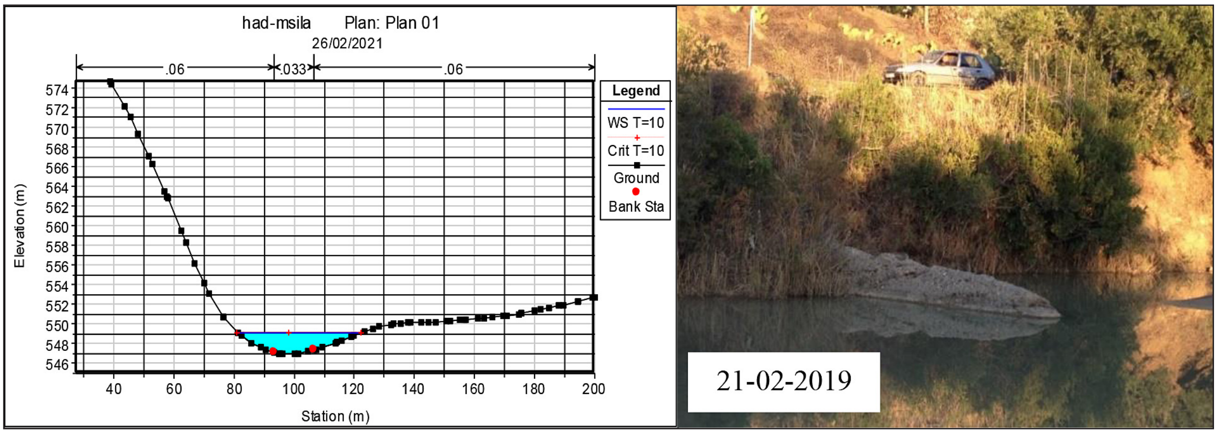

Figure 6. (a) water level reached and wetted width by the decadal flood of the Oued Lahdar; (b) situation of road RR508 at the meander level

on November 29 amounted to 102.4 mm. The soil, already saturated by the preceding days' rainfall, could no longer absorb any more water. These floods caused damage to homes and infrastructure. Adjusting this value using the Gumbel law yielded discharge results of 566.68 m^3/s, corresponding to the twenty-year flood. The twenty-year flood resulted in some overflows observed on the P5414 road on the right bank of the Oued Lahdar (Figure 7b). Figure 7a shows that the maximum overflow height relative to the upper edge of the right bank is 2.5m. On the left bank side, this flood affected developed areas and areas occupied by non-hydrophilic vegetation cover, such as olive fields. Along the Oued Lahdar, a number of human installations have been built in the alluvial plain. This type of land use increases the vulnerability of settlements to the risk of flooding, especially during twenty-year floods.

- fifty-year flood – with a return period of 50 years, the risk of flooding on these lands in the alluvial plain of the Oued Lahdar is considered moderate. The results of flood estimation for the 50-year period yield discharge values of 761.22 m^3/s for the Oued Lahdar and 290.41 m^3/s for the Oued Rhnalla (a right-bank tributary of the Oued Lahdar). These discharges can be reached when rainfall in the Lahdar watershed exceeds 116.5 mm/day. Some floods recorded in the watershed with a fifty-year frequency have exposed human settlements, and several hydro-agricultural infrastructures have been damaged, leading to the loss of many livestock heads. Notably, those of December 23, 2010. Hydraulic simulation shows that the water level produced by the fifty-year flood of the Oued Rhnalla reaches a level of 559.5 m (Fig.8a), causing a 1-meter overflow on the bridge connecting

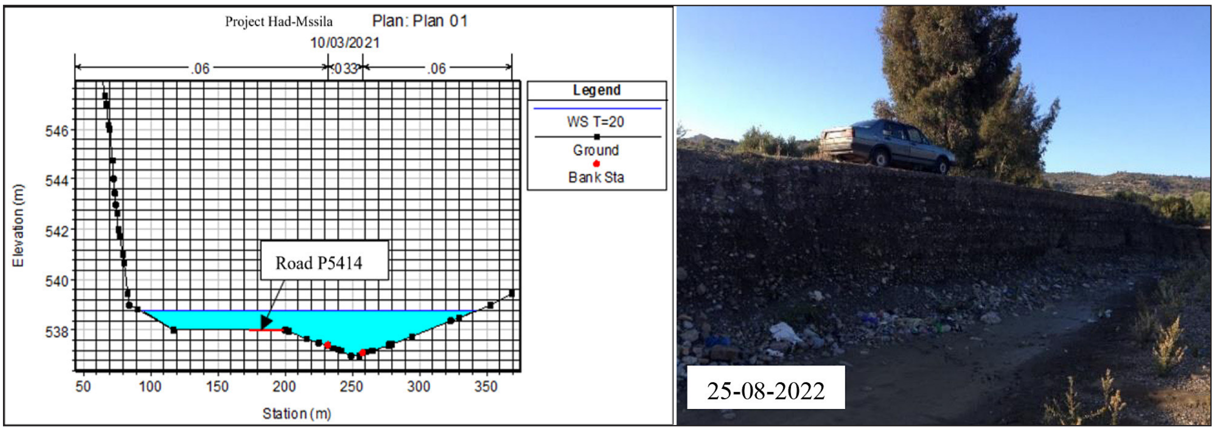

Figure 7. (a) water level reached and wetted width by the twenty-year flood of the Oued Lahdar, (b) situation of road RP5414

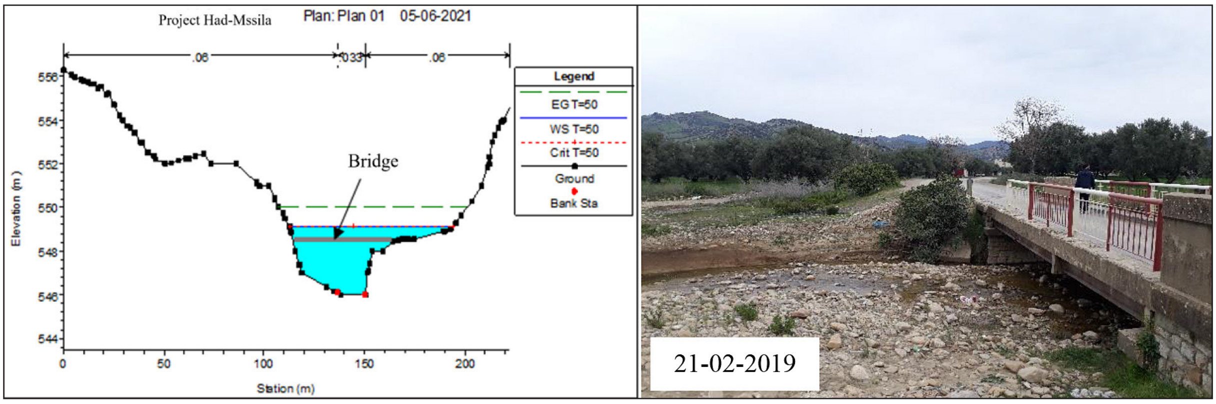

Figure 8. (a) water level reached and wetted width by the fifty-year flood of the Oued Rhnalla; (b) situation of the bridge connecting Had Msila and the city of Taza (RR508

Had Msila to the city of Taza (Figure 8b).In terms of the geographical consequences of the flood, overflow of the Oued has been observed in several sections crossing the Center of Had Msila, inundating multiple streets and residences. The magnitude of the flow and water levels has led to the destruction of several bridges in the Center of Had Msila and submerged roadways as well as residences located along the Oued.

- centennial flood and millennial flood – the estimation of centennial and millennial floods by hydrological models in the Lahdar alluvial plain has led to obtaining high discharge values. These discharges, although rare, remain possible and dangerous. They would result in more extensive flooding and the submersion of vast areas of the Had Msila Center, including residences, public establishments, mosques, the new weekly market, etc. The results obtained from the statistical fitting of the Gumbel law provide the amount of rainfall conducive to the centennial flood, exceeding 146.1 mm/day, and 186.1 mm/day corresponding to millennial floods, at the Oued Lahdar. Inhabitants occupying lands near the Oued are exposed to increased risk. In the event of a possible centennial flood, the flooding would be formidable, resulting in significant damage. The affected area would be more extensive, and the damage would affect not only residences but also recently constructed infrastructure such as roads, public establishments (agricultural center, new weekly market.). The passage of the centennial flood causes overflows in the canalized section just upstream of the mosque bridge in the Had Msila region (Figure 9b). The modeling of the centennial flood of the Oued Lahdar at the Had Msila Center (Fig. 9a) shows that the maximum overflow height relative to the upper edges of the Oued Lahdar banks is 4.5 m. Regarding the downstream section of the Had Msila Center, at the passage of the P5414 road, overflow is observed during millennial floods, with very

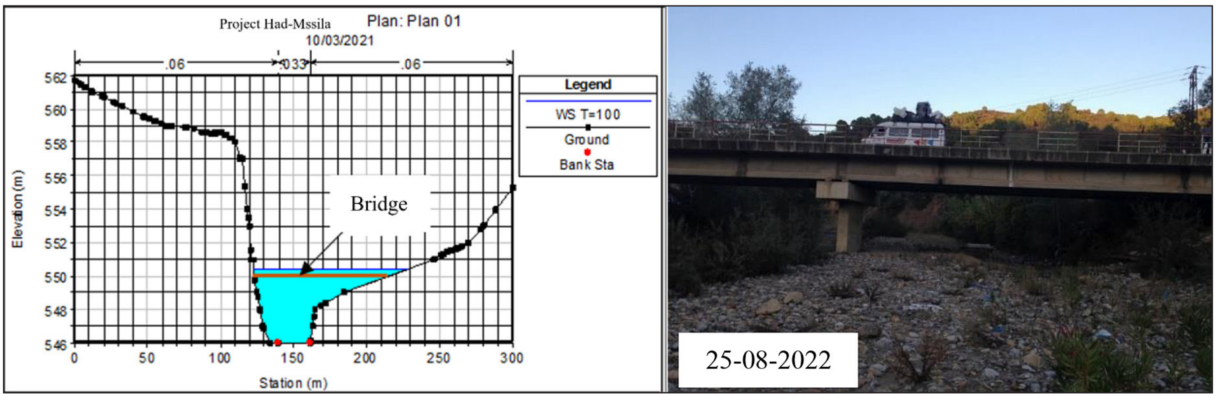

Figure 9. (a) water level reached and wetted width by the centennial flood of the Oued Lahdar; (b) situation of the mosque bridge (RR508)

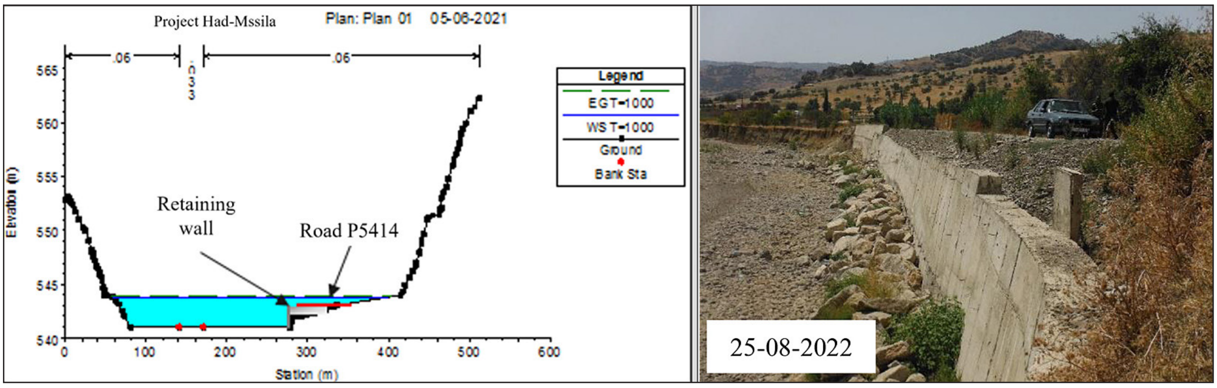

Figure 10. (a) water level reached and wetted width by the millennial flood of the Oued Lahdar, (b) situation of the retaining wall protecting road RP5414

significant flooding at this level. Figure 10a clearly illustrates the flooding of the road and the rapid rise of water levels up to 2.5 m at the retaining walls (Figure 10b). Numerous sites in the modeled sectors were inundated by the waters of this flood. The road network of the Center was also disrupted due to heavy precipitation in the region. Additionally, infrastructural damage was recorded, including the destruction of several retaining walls, the submersion of certain bridges, and the scouring of banks as well as their protective dikes. The floods have had damaging effects on several public establishments, causing disruptions in their operations and leading to considerable repair costs. The Had Msila Center Hospital, in particular, was severely affected by the floods, impacting its ability to provide essential medical care and requiring significant rehabilitation efforts to fully restore its services.

CONCLUSIONS

Hydraulic flood modeling currently stands as one of the most commonly used methods for flood risk mapping. Implementing this method requires data of high precision. In our study, the collection of geometric data and determination of hydraulic parameters were carried out with meticulous care, requiring laborious and detailed work. This rigorous effort yielded convincing results, validated through comparisons with field observations (phenomenon mapping).

This hydraulic model highlighted the significance of flood risk in the studied area and allowed for estimating the impact of floods for return periods of 10, 20, 50, 100, and 1000 years. It constitutes an essential preliminary step for the development of an indicative flood hazard map. Besides diagnosing flood-prone areas, it serves as a basis for controlling and validating the results of hydraulic flood simulations. These simulations provide cartographic data on flood extents, as well as their heights and velocities. The model also facilitated assessing the vulnerability of hydraulic infrastructures, such as bridges, to past and future floods.The results of hydraulic modeling contribute to establishing the map of flood risk areas in the Lahdar River valley, particularly at the level of urban areas and infrastructure. These results allow for spatializing flood risk in the Lahdar River watershed, which can be useful for decision-makers when selecting sites and types of hydraulic development, taking into account the characterization of the hydrological regime, whether for project flow or peak flows for different return periods.

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