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Flood Risk Assessment Basing on Flood Flow Modeling in the Oued Martil Region, Western Part of Northern Morocco

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ABSTRACT

In the context of climate change, the risk of flooding is becoming an increasingly global concern. In addition, natural factors, economic development and urban expansion are significant contributors that have generated a strong demand for the management of natural risks, especially in the domain of floods and inundations. This research aims to address the issue of flood risk management in the Oued Martil region, specifically within the cities of Tetouan and Martil in the western part of Northern Morocco. In this regard, this study focuses on evaluating the performance of hydrological analysis of the Oued Martil plain and modeling flood flows in the Oued bed and in the plain overflow area. The results of this study show that the risk of flooding is significant in urbanized and densely populated areas (with high vulnerability) that match with zones with high or moderate hazard. Conversely, the risk of damage is lower for forests situated in areas with low or moderate hazard. The results obtained from hydraulic modeling can assist decision-makers in selecting the types of interventions for floodplain development by providing a comprehensive understanding of Oued Martil's behavior during the exceedance of peak flow rates for different return periods.

Keywords: climate change, risk of flooding, Oued Martil, hydrological models, Tetouan.

INTRODUCTION

In the world, climate change is the main cause of natural disasters [Banholzer et al., 2014; Berlemann and Steinhardt, 2017]. The frequency of these disasters, including the risk of flooding, is amplified by climate warming [Fowler and Hennessy, 1995; Karim and Mimura, 2008; IPCC, 2013; Tabari et al., 2021; Liu et al., 2023]. Since 1990, natural hazards have resulted in over 1.6 million fatalities worldwide and have led to an annual economic loss of approximately $260-310 billion [Ward et al., 2020]. Floods are basically extreme hydrological events due to heavy precipitation. Flood risk is a global problem that affects the entire countries of the world with different degrees. Flood is one of the most common natural disasters, causing significant damage to people, infrastructure, climate and economies. It's also triggering other natural disasters such as erosion, landslides, water and soil pollution, etc. Over the past 20 years, flooding accounted for approximately 43% of natural disasters and had a significant impact on nearly 2.5 billion people worldwide [CRED, 2015; Dottori et al., 2018].

The Mediterranean region has experienced multiple floods that are becoming an increasingly formidable threat. Precipitation in this region often exceeds 200 millimeters within 24 hours [Ducrocq, 2006; Lionello, 2012; Albatayneh, 2023], and sometimes even within six hours. Over the past sixty years, Morocco has experienced major floods that have caused significant economic damage in several regions. It has recorded no less than 35 episodes of flooding between 1951 and 2015 [Zurich, 2014]. The catastrophic events in the Ourika Valley in 1995, the city of Tétouan and the Martil plain in 2000, the regions of Chaouia (Mohammadia, Berrechid, and Settat) in 2002, the region of Tanger in 2008, the Gharb plain in 2009 and 2010, the region of Taza in 2010 and 2018, the region of Khénifra in 2011, and Guelmim and Sidi Ifni in 2014 bear witness to the extent of these floods.

Floods pose a threat to the safety and health of the residents in the northern region of Morocco, as well as to the economy and infrastructure. They can result in loss of human lives, significant property damage, and economic disruptions, and also disrupt public services such as transportation, communications, and trade, thereby affecting all socio-economic activities. The issue of flooding in the study area is of major importance for local, regional, and central authorities, as well as for the residents of the region. Therefore, it is crucial to understand the causes of these floods and propose solutions to mitigate the impact of risks. The choice of the study area highlights the detrimental effects of climate change in Morocco, as historically, the region has been prone to flooding since the 1960s until today. Episodes of flooding have been recorded at very close intervals [Mathieu, 1964].

The main objective of this study is the mapping of flood risk zones and implementation of protection measures. Therefore, prioritizing sub-watersheds is one of the chief measures for sustainable management of watersheds, with the purpose of controlling the flood [Nafarzadegan et al., 2019]. Flood prioritization is a complex task that requires the integration of various factors and data sources. Traditional flood management approaches often rely on single criteria, such as historical flood records or topographic characteristics, which may not capture the full complexity of flood dynamics. Furthermore, the availability and quality of data in the Oued Martil watershed may pose challenges, necessitating the use of innovative methodologies that can overcome these limitations. Geomorphometric properties [Ghasemlounia and Utlu, 2021]. For this purpose, several methods have been used, such as Morphometric analysis (MA) approach [Meshram et al., 2022], Multi-criteria decision-making (MCDM) methods [Kanani-Sadat et al., 2019; Nasiri Khiavi et al., 2023], Analytic hierarchy process (AHP) [Lin et al., 2020; Wijesinghe et al., 2023], hydrological studies [Natarajan et al., 2020; Talukdar et al., 2023], FUZZY-AHP approach [Yang et al., 2018; Sayyad et al., 2022] and the analytic network process (ANP) [Yariyan et al., 2020; Chukwuma et al., 2023], are utilized as techniques to identify areas with a high potential for producing floods. This study suggests using a hydrological study approach for Oued Martil and its tributaries, ranging from Oued Khémis to the river mouth, in response to the challenges associated with flood mapping in the study area. With this plan, Tetouan city and the Martil plain will be better protected against flooding caused by the Oued Martil.

The findings of this study will provide valuable insights for managers and decision-makers in developing action plans and flood risk management strategies. These strategies must consider the varying impacts on populations based on their social, economic, and environmental vulnerabilities. Additionally, an environmental justice perspective should be integrated to ensure that all communities benefit from protection and resilience measures against flooding.

MATERIALS AND METHODS

Study area

The study area is located between Tamouda bridge and the river mouth. It is part of the Tetouan province, encompassing the municipalities of Tetouan Al Azhar and Sidi Al Mandri (Fig. 1). The section of the Martil River under consideration in this study flows from southeast to northeast, traversing the southern part of the city of Tetouan. The latter is situated at the northernmost point of the kingdom of Morocco, approximately 60 kilometers east of the city of Tangier on the road to Ceuta, near the Strait of Gibraltar. Utilizing data from December 2000 Tetouan flood gives considerable historical context for grasping climate patterns and trends, even after 23 years have passed.

Contrasting contemporary conditions with those of more than twenty years ago may highlight major variances and help forecast future trends. Moreover, utilizing data from the year 2000 as a reference point helps researchers to examine the advancement of meteorological conditions across time. This comparison is critical for discovering trends and measuring the effect of climate change. As climate change is a long-term process, and studying data over decades is vital for understanding its trajectory properly, various

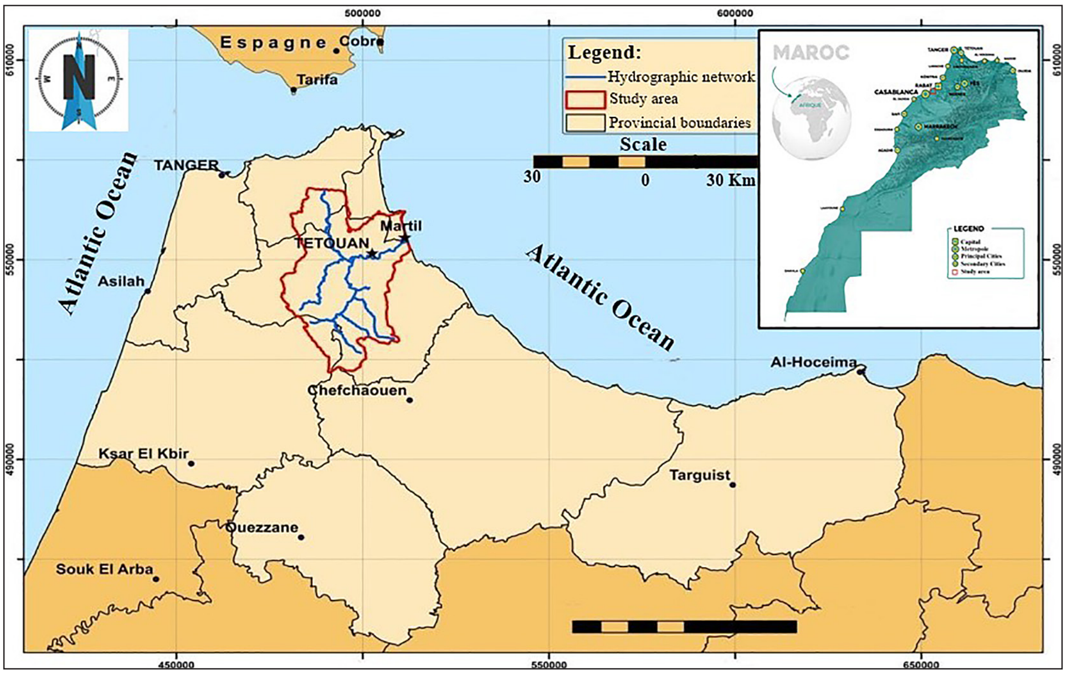

Figure 1. Location map of the study area

activities are in way at our laboratory that is going to handle data from 2000 till today. This study effort between Mohamed V university and Abdelmalek Essaadi university will take into account newer data so as to properly understand the risk flood behavior in the scrutinized location.

Study variables

Geomorphology setting

From a geomorphological perspective, the western portion of the Rif Mountain range, which is largely covered by the province of Tetouan, has a topography that is extremely rocky and turbulent. A few low-lying places and a small number of Mediterranean plains, such those in Martil, Ajras, Oued Laou, and Mallalyenne, are exceptions. However, the internal basins, corridors, and valleys, where the topography is often hilly or semi-flat, pierce the mountainous backbone in certain places. The distribution of the province's land area by type of terrain is as follows: mountains – 70%, hills – 15%, Valleys/depressions: 10%, plains and plateaus – 5%. The study area is part of the Martil River plain, as illustrated in the Figure below (Fig. 2).

The Oued Martil watershed extends over a geographical area characterized by a predominantly mountainous landscape (Fig. 3a) with a very rugged and tormented topography, with the

Figure 2. Relief of the study area and location of the section of Oued Martil

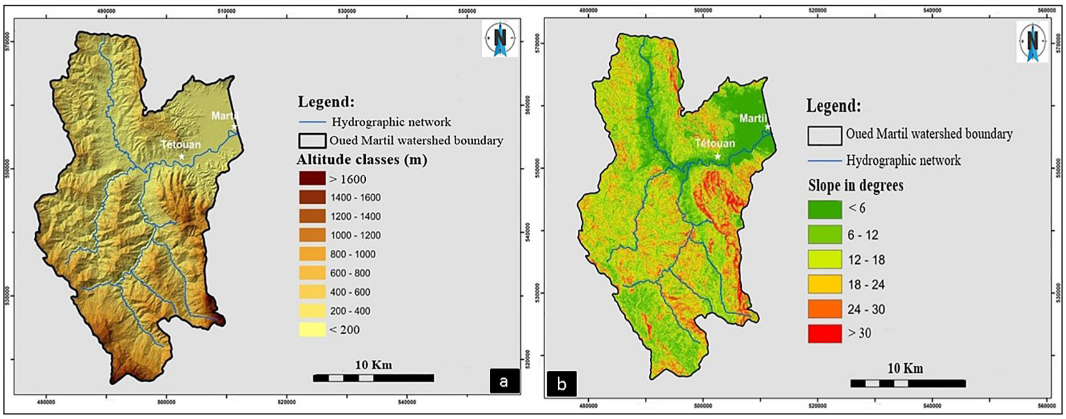

Figure 3. Hypsometry (a) and slopes (b) of the Oued Martil watershed

exception of certain areas of low relief and a few very small Mediterranean plains, such as the Martil plain. Slopes (Fig. 3b) are highly variable, due to the area's position between the Rif Mountain range and the Mediterranean Sea.

Geological setting

The Rif chain, located in northern Morocco, is a part of the Alpine system of the Western Mediterranean. It is extended through southern Spain's Betic Cordilleras toward the north. From a structural standpoint, the Rif is separated into three domains: the internal domain, the Flysch domain, and the external domain, which run from the interior to the exterior of the chain [Michael, 1976; Suter, 1980].

The plain of Martil, one of these peripheral basins and the subject of our investigation, is situated in the internal domain of the Rif chain, which is distinguished by its complicated tectonic structure and stratigraphic patterns (Fig. 4). When pull-apart systems were triggered in the late Miocene by a N-S oriented compressive phase [Benmakhlouf and Chalouan, 1994; Romagny, 2014], this domain, which was primarily formed by Paleozoic material of the Sebtides and Ghomarides units [Durand Delga and Kornprobst, 1963; Didon et al., 1973], was subject to extensional deformation. Since then, a thick layer of sedimentation covering the Paleozoic substratum on the Martil plain dates back to the Quaternary. According to seismic profiles and field data, sedimentary layers

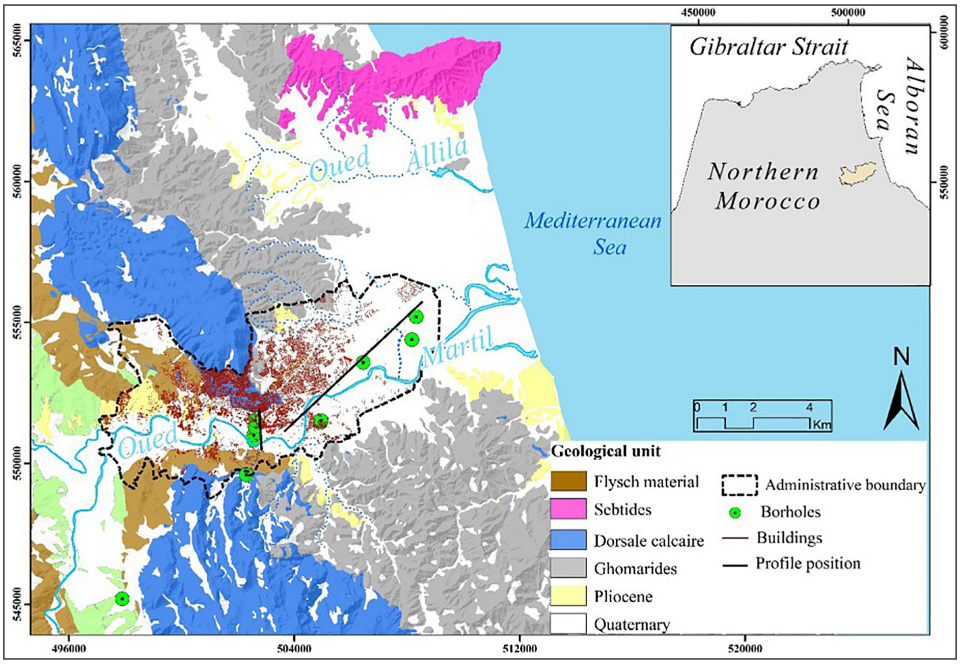

Figure 4. Geological map of the study area

cover a graben and horst structure that was part of two extensional deformation episodes, one in the late Oligocene and the other in the late Miocene [Ouazani Touhami et al., 1994; Romgny, 2014].

The geology of the urban center of Tetouan (Fig. 4) and its surroundings is characterized from east to west by a stack of west-verging thrust sheets that thrust the internal domain into the flysch domain and the external domain. The internal domain outcrops in the East with Ghomarides metamorphic terrains that carry the tectonic scales of the external limestone ridge of Jbel Dersa (northern Tetouan). The Flysch domain is represented by the Beni Ider groundwater in the west and the Predorsalian along the Martil valley.

Climatic setting

The climate of the region is Mediterranean with oceanic influence. It is characterized by mild winter and summer temperatures due to the proximity of the sea (with average maximum temperatures around 23 °C and average minimum temperatures around 14 °C). The region also receives an average annual precipitation of approximately 650 mm, although these average values do not capture the intermittent nature of the rainfall. Winds from the east (Charki) prevail from May to October, while those from the west (Gharbi) dominate from October to February. From March to April, a balanced pattern of winds from the ENE and WSW sectors is established.

The aforementioned average values do not in any way reflect the random and contrasting nature of the climate in the Tetouan and Martil cities within the broader climatic context of Morocco. Indeed, the precipitation regime exhibits both seasonal and annual contrasts, whether it's in terms of averages or maximum precipitation levels. Amidst this temporal irregularity, episodes of extreme weather conditions stand out, such as the low rainfall in the 1940s, with only 1246 mm in 1955/56 compared to 446 mm in 1956/57, a remarkable 632 mm in a single month (March 1962), a rapid 300 mm in just 3 hours in Fnideq (December 1990), and 160 mm in 12 hours in September 1994. Consequently, alongside periods of drought and water scarcity resulting from this variability, there are excessively rainy periods with significant, short-duration thunderstorms responsible for flooding, river surges, and landslides (Fig. 5).

Hydrological setting

The hydrological context of study area, is subdivided into two parts: surface water resources and groundwater resources:

- surface water resources: A densely interconnected hydrographic network, which includes the Oued Martil, is produced as a result of the region's heavy rainfall, non-porous ground cover, and hilly topography. Its annual average inflow is thought to be around 540 million cubic meters. However, there is a lot of variability in the hydrological pattern, and this variability is closely related to the amount of precipitation. Notably, December through February tend to have the biggest inflows (Fig. 6).
- groundwater resources: The majority of the region is covered by impermeable or poorly permeable lithologies, which makes it difficult for extensive continuous aquifer formations to exist. There are a few isolated tiny basins, alluvial valleys, and limestone formations that are exceptions to this rule. The primary aquifers can be divided into two categories: (i) Alluvial aquifers, which are significant locally and are vulnerable to overuse, saltwater incursion, and

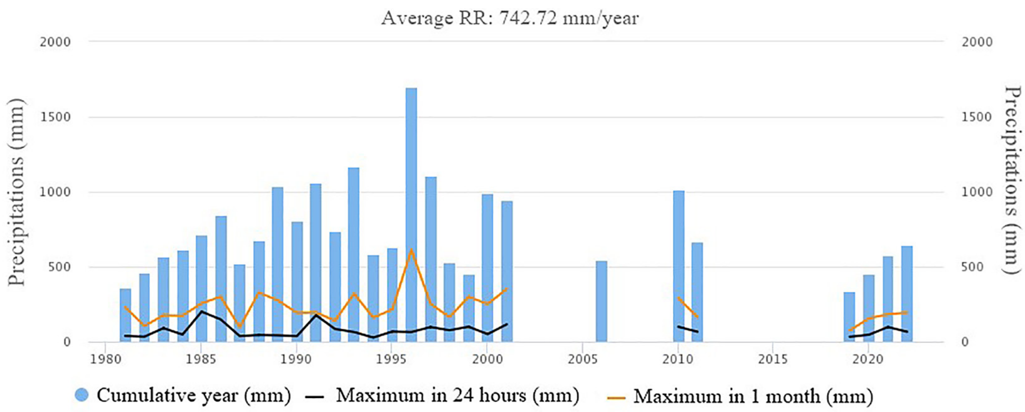

Figure 5. Rainfall in the study area, Tetouan / Sania Ramel station (1980–2020)

pollution. The Martil-Allila, Amsa, and Oued Laou aquifers are notable examples. (ii) Limestone formations, which have a lot of potential for holding water and act as a reservoir for the area. These can be further separated into the limestone ridge to the southeast of the city of Tetouan and the Haouz chain, which is located between Belyounech and Tetouan.

METHODOLOGY

Hydrological studies of the Oued Martil watershed

The hydrological analysis of Oued Martil and its tributaries was initially conducted as a component of the hydraulic investigation of Oued Martil, spanning from its confluence with Oued Khémis to its estuary in 2004 [Loukkos Water Basin Agency, 2004]. Subsequently, a repeat study was carried out within the context of safeguarding the city of Tetouan and the Martil plain from Oued Martil flooding in 2005 [Loukkos Water Basin Agency, 2003]. The results of these studies are summarized below, distinguishing between: (i) large basins, i.e., the Oued Martil and its tributaries upstream of the city entrance, and the oueds that flow into it as they cross the city (Fig. 7; Table 1); (ii) small basins: these are the peri-urban and urban basins that dominate the wadi valley as it crosses the town and flows into the sea; (iii) the impact of the Koudiat Gensoura dam on Oued Martil flooding. Following the results of the hydrological study, the typical flood hydrograph is that of the USSCS applicable to the Torrita bridge (Martil), at the confluence of the Khémis and Mhajrate rivers, the USSCS hydrograph, featuring an 8-hour rising time, was selected as the representative hydrograph for Oued Martil flood events (Fig. 8).

Hydraulic study of the Martil Wadi from the confluence with the Khémis wadi to its mouth

This study was conducted using a flood flow model for both the wadi bed and the plain overflow area. To achieve this, a digital terrain model (DEM) was essential, which was created based on city survey data at a 1/2000 scale. The software employed for this purpose was Mike 11, developed by the Danish Hydraulic Institute (DHI). In order to model Oued Martil, a straightforward one-dimensional approach relying on cross-sectional profiles perpendicular to the flow was adopted.For the simulation of floodplains, the Coastal Institute (CI) utilized a two-dimensional "pseudo" model to account for interactions between different channels. The slope of overflow from Wadi Martil towards the Martil plain on the left bank of RS607 is 4.70 NGM. Additionally, hydraulic structures were integrated into the model, including the new Tamouda bridge, the old Tamouda bridge, the former Torreta bridge, and the RS608 bridge. Downstream model conditions were taken into consideration to demonstrate the influence of tidal effects on the calculation results. We decided to explore two scenarios: (i) sinusoidal tide with a maximum of H = 0.9 m

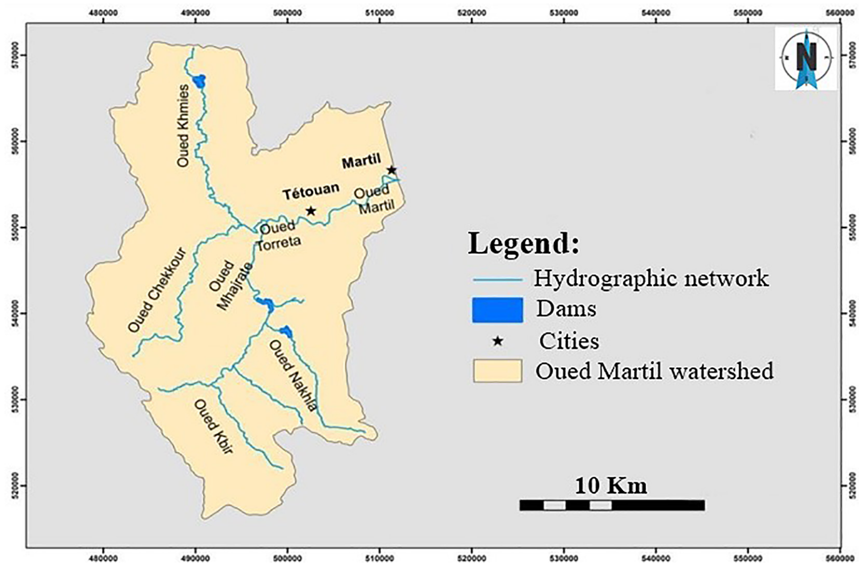

Figure 6. Oued Martil watershed hydrographic network

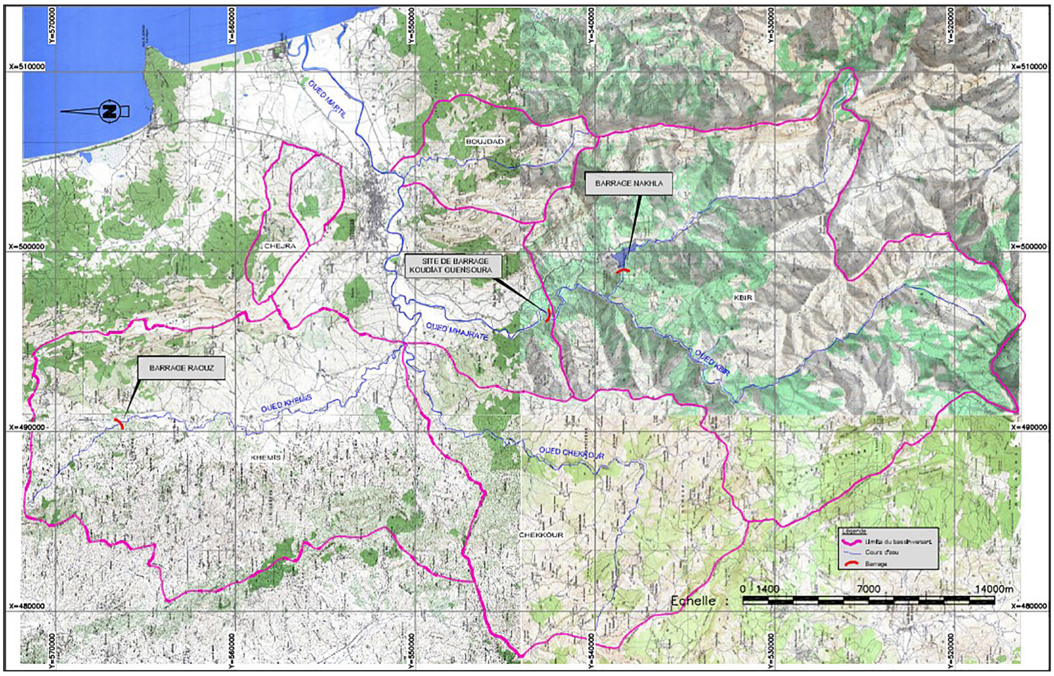

Figure 7. Map of major basins in the study area

Table 1. Results of the hydrological study of major watersheds

Oueds	Surface (km²)	Flow & volume	10 years	20 years	50 years	100 years	1000 years	10000 years
Chejra	17	Qp (m^3/s)	60	80	150	180	270	370
		V (Mm^3)	0.38	0.51	0.95	1.14	1.71	2.34
Boujdad	49	Qp (m^3/s)	120	155	270	320	470	630
		V (Mm^3)	0.64	0.83	1.45	1.72	2.52	3.38
Chekkour	197	Qp (m^3/s)	460	540	670	770	1 100	1 440
		V(Mm^3)	13	16	20	22	32	42
Khémis	290	Qp (m^3/s)	890	1 080	1 430	1 650	2 370	3 100
		V (Mm^3)	35	42	56	64	92	121
Mhajrate	383	Qp (m^3/s)	610	730	1 170	1 370	2 040	2 720
		V (Mm^3)	18	21	34	40	60	80
Martil à Pont Torreta	1073	Qp (m^3/s)	1 570	1 900	2 460	2 790	3 870	4 960
		V (Mm^3)	69	83	108	122	170	218

NGM (corresponding to high tide, as per [Loukkos Water Basin Agency, 2003]); (ii) constant tide: H = 1.9 m NGM (high tide based on [Loukkos Water Basin Agency, 2003], an additional 1 m to count for atmospheric conditions and swell's braking effect). Furthermore, the following assumptions were made: (i) the upstream flood input is based on the December 2000 flood; (ii) the roughness value was determined using the Ven Te Chow method.

Model calibration

This calibration process is anchored in data gathered during the December 2000 flood. The input hydrographs for the model encompass: Hydrographs observed at the Ben Karrich and Amzal hydrometric stations. A reconstructed hydrograph of Oued Khémis, specifically the USSCS hydrograph, derived from the maximum discharge recorded at the Boussfiha bridge (1470 m^3/s).

Downstream model condition

The impact of tides on maximum water levels is deemed minimal. Consequently, the tide at Sebta was adopted as the downstream model condition, accurately reflecting the conditions during the 2000 flood.

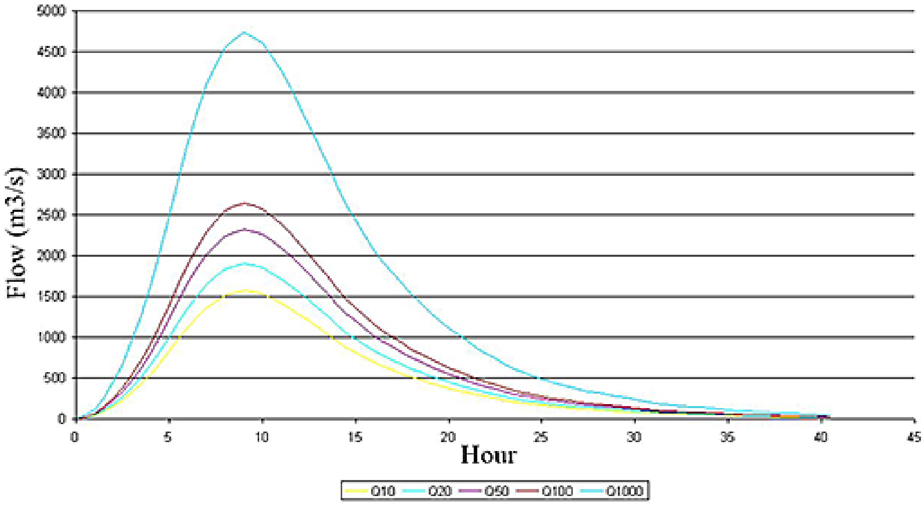

Figure 8. Flood hydrograph water level Torreta Pont (Martil City)

Urban tributaries of Wadi Martil

The model representing the 2000 flood did not incorporate the urban tributaries of Oued Martil due to the scarcity of information and an estimated negligible impact, resulting in a projected increase in water level ranging from 10 to 25 cm. For the present study, the Strickler coefficients used are as follows: Variable K, according to Ven Te Chow's analysis and Variable K of scenario 1 reduced by 15%.

The impact of the new bus station of Tetouan was also analyzed on the basis of the hydraulic model. It raises the water level upstream of the Torreta bridge by around 30 cm. The water level is then equal to 11.3 NGM at this level, and the bus station platform (at 11 NGM) would be flooded in a event similar to the December 2000 flood. The following figure (Fig. 9) shows the simulated water level upstream of the Torreta bridge for simulations of the 2000 flood with (blue) and without (black) the bus station development.

The simulation with a variable strickler K, according to Ven Te Chow's analysis, is the one that best simulates observations of the water levels of the December 2000 flood reached at different locations in the valley. Each development in the

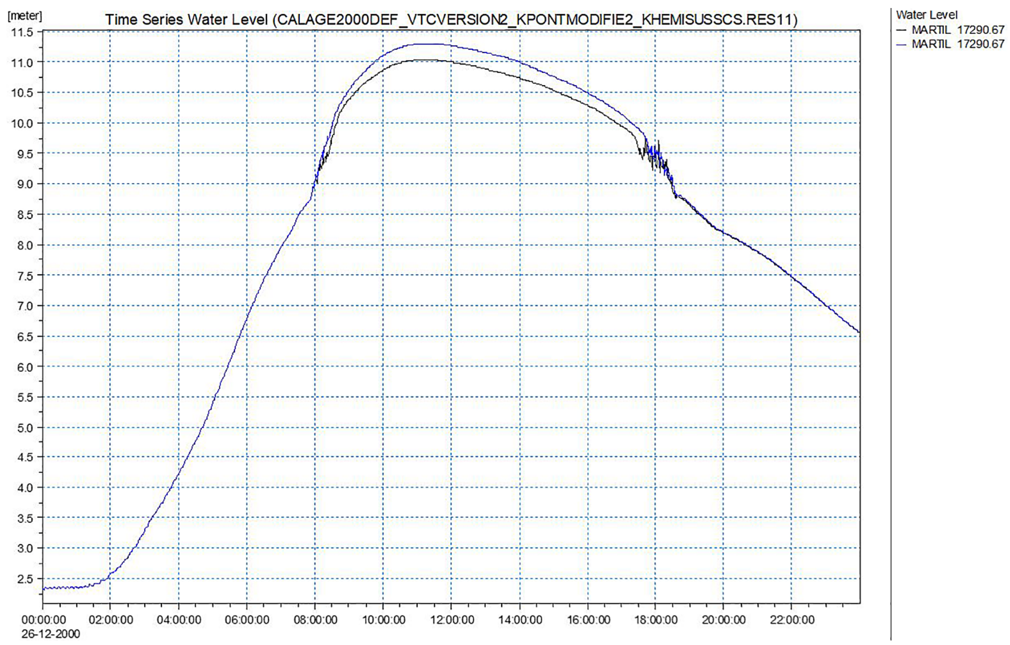

Figure 9. Simulated water level upstream of Torreta bridge for 2000 flood simulations

Martil valley can affect the water levels reached in the valley in the event of a flood similar to that of December 2000. The following figure (Fig. 10) shows the flood map, zooming in on the section of Oued Martil between the Tamouda bridge and the bridge over the RS608.

During the 2000 flood, the main channel of Oued Martil experienced varying levels of inundation, which included: (i) water levels rose from 0.5 to 2 meters both upstream and downstream of the Tamouda bridge; (ii) upstream of the Torreta bridge, water levels reached 1 to 2.5 meters; (iii) downstream of the Torreta bridge, water levels ranged from 0.5 to 1 meter; (iv) upstream of the RS608 bridge on the right bank of the wadi, water levels reached 1 to 2 meters, leading to flooding in the Couelma district; (v) downstream of the RS608 bridge on the right bank of the wadi, water levels varied from 0.5 to 1 meter.

It's important to note that none of the three bridges (Torreta, Tamouda, and the bridge over RS608) were submerged. However, the access roads to these bridges were underwater, except for the access road on the left bank of the bridge over RS608. A detailed flood map, focusing on the Oued Martil section between the RS608 bridge and the river mouth, is provided in Figure 11.

During the 2000 flood, the following observations were made: The Oued Martil valley experienced inundation with water levels ranging from

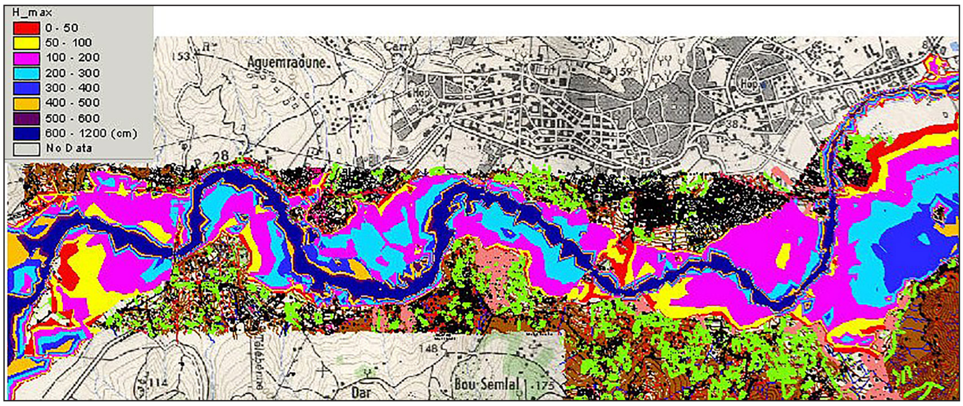

Figure 10. Flood map for the December 2000 flood Zoom on the upstream section of Oued Martil

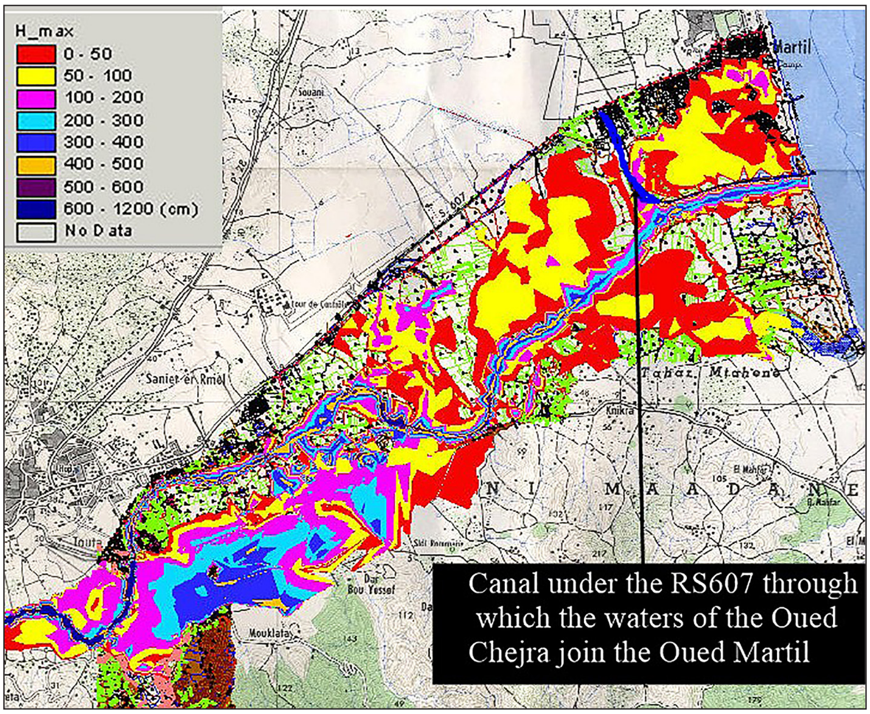

Figure 11. Flood map for the December 2000 flood Zoom on the downstream part of Oued Martil

0.5 to 2.5 meters. The floodwaters from this event inundated the Diza district, situated at the river mouth, with water heights ranging from 0.5 to 1 meter. Notably, he floodwaters did not reach the RS607 road leading to Martil.

Oued Martil flood simulations and maps for 100-year flooding

Simulations and flood maps have been developed for Oued Martil, depicting the conditions during a 100-year flood event. This model provides insights into the occurrence of 100-year floods in the Martil valley, encompassing the Oueds Martil, Samsa, and Boujdad. The following table (Table 2 and Fig. 12) summarizes the peak flows of the 100-year floods of the Martil (at the confluence of the Khémis and Mhajrate Oueds), Samsa and Boujdad Oueds. During the passage of a 100-year flood, the main bed of the Oued Martil was inundated at varying heights: From 0.5 to 2 meters of water upstream and downstream of the Tamouda bridge. From 1 to 2.5 meters of water upstream of the Torreta bridge. From 0.5 to 1.5 meters of water downstream of the Torreta bridge. From 1 to 2 meters of water upstream of the RS608 bridge on the right bank of the wadi. This resulted in the flooding of the Coelma district. From 0.5 to 1.5 meters of water downstream of the RS608 bridge on the right bank of the Oued (Fig. 13).

Through this channel, the waters of the Oued Martil flood part of the left bank of the RS607: water level at 2.13 NGM (given the availability of only 1:50,000 topographical information and the flat nature of this area, it is not possible to draw the outline of the flood map in this zone). It’s observed that during the occurrence of a 100-year flood: The Oued Martil valley experienced flooding with water levels ranging from 0.5 to 2.5 meters. The floodwaters from this event inundated the Diza district, situated at the river mouth, with water heights ranging from 0.5 to 1 meter. Importantly, the floodwaters did not reach the RS607 road leading to Martil.

CONCLUSIONS

The study on flood risk management in the Oued Martil region, Northern Morocco in the year of 2000 provided crucial insights into the dynamics of flooding in the area. Through a comprehensive evaluation of hydrological analysis and flood flow modeling, this paper has identified significant risks of flooding, particularly in urbanized and densely populated areas. This highlights the vulnerability of communities to the adverse impacts of flooding, including damage to infrastructure, loss of livelihoods, and threats to human lives. This assessment is based on data from December 2000 to simulate the flood flow in the Oued Martil valley. The valley had a flooding calamity with water levels ranging from 0.5 to 2.5 meters. High-risk flooding is significant in urbanized and densely inhabited places like Tetouan and Martil

Table 2. Peak flows of the 100-year floods of Oued Martil and its tributaries

Flow (m^3/s)	Martil	Samsa	Boujdad
Q100	2820	115	320

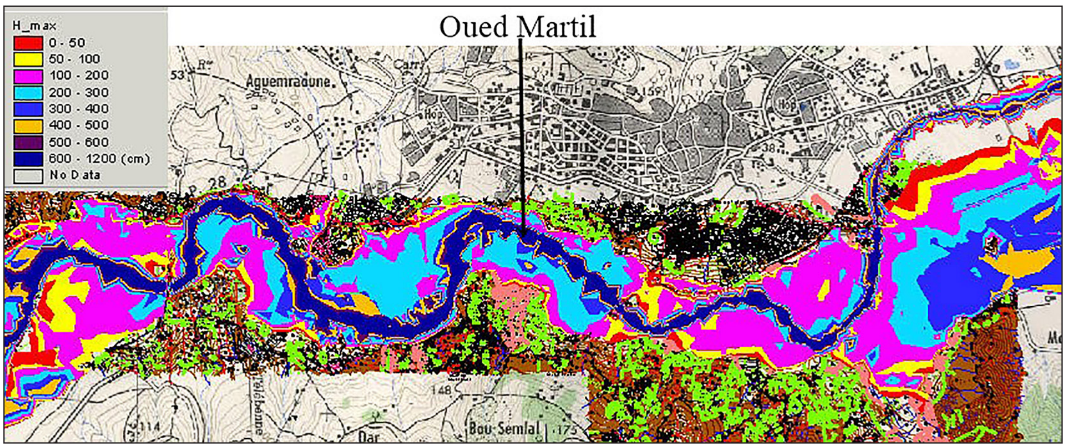

Figure 12. Flood map for the 100-year flood of Oued Martil - Focus on the upstream section

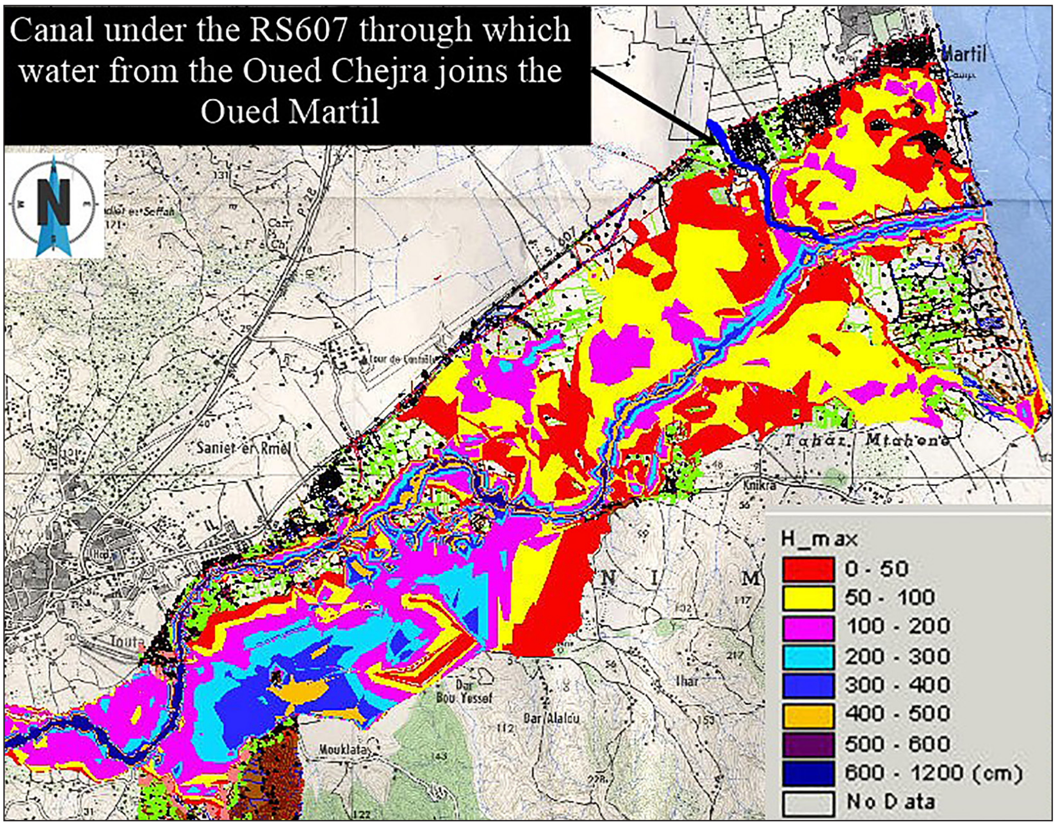

Figure 13. Flood map for the 100-year flood of Oued Martil - Focus on the downstream section

in the Oued Martil zone, whereas the danger of damage is modest in forested areas with low to moderate sensitivity. The flood water did not impact the RS607 road to Martil. Moreover, to elucidate the high susceptibility to floods in the area under investigation, many key aspects have been thoroughly examined. The region's vulnerability to flooding is due to its mountainous topography, impermeable geological formations, high and concentrated precipitation, extensive hydrographic network, and hydrological regime characterized by sudden and often severe floods with unusually low water levels. Flood discharge rates rapidly approach critical levels, particularly in the alluvial plains near the Martil River's outflow, where the most severe losses occur. However, we must not overlook how human activity considerably raises the danger of floods. The natural hydrological balance of Tetouan and Martil has been disrupted by the construction of urban populations and infrastructure along, and sometimes even within, the minor and main beds of the Martil River. When soil impermeability is paired with intense and short precipitation episodes, the likelihood of dam erosion and sedimentation rises. The challenge is made more harder by the sanitation network's deficiencies. Interestingly, the study also revealed a lower risk of damage for forests compared to urbanized areas. This finding underscores the importance of considering land use and vegetation cover in flood risk management strategies. Forests and natural vegetation can serve as natural buffers against flooding by absorbing excess water, reducing soil erosion, and mitigating the intensity of flood events. Effective emergency management is necessary due to the imminent threat of floods. It is vital that key authorities and decision-makers adopt flood mitigation measures and disaster management plans in order to properly handle this problem. Strong drainage systems, land-use restrictions that prohibit development in high-risk zones, protecting forests and natural vegetation, early warning systems, public education campaigns about flood preparation, and thorough crisis management protocols are a few examples of viable solutions. Active coordination between local government, disaster management specialists, and the community is important to create a coordinated and successful response to this reoccurring danger. All in all, the conclusions of this research, which is founded on Oued Martil behavior during peak flow rates for various return periods, may serve as a guide to enable decision-makers to choose the appropriate floodplain management actions.

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