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Mapping and Zoning of Flood Hazard: Case Study of the Ouad Lahdar Valley at the Meknassa Al Gharbiya Territorial Center, Upper Inaouene, Morocco (Application of the Hydrogeomorphological Method)

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Abstract. The present study aims to map flood hazard in the Ouad valley, specifically focusing on the Meknassa El Gharbiya Territorial Center (the downstream part of the Ouad Lahdar watershed). This approach relies on the application of the hydrogeomorphological method, whose results have been validated and adopted in other countries. The study refers to the 2010 flood, considered the most devastating and causing considerable damage. It utilizes data from photo interpretation, satellite image analysis, as well as field observations and surveys.

Following its application in the Ouad Lahdar watershed, where it yielded promising results, the study seeks to delineate flood-prone areas in the Ouad valley, at the level of the Meknassa El Gharbiya Territorial Center. Additionally, it aims to identify dynamics influencing the various documented flood beds. This approach underscores the importance of a thorough understanding of the processes governing the evolution of the alluvial plain for accurate assessment of flood risks in each territory. Flood risks in the alluvial plain of the Ouad Lahdar vary according to the characteristics of the different geomorphological units present in this area.

Key words: Catchment, Lahdar River, Flood risk, Hydrometeorological method, Cartography

Introduction

River floods remain a persistent challenge affecting vast populations worldwide on a recurrent basis. Despite numerous initiatives aimed at reducing their adverse effects on residents and their properties, the socio-economic damages they cause continue to escalate, both in developed nations and in developing countries. Today, the increasing occupation of flood-prone areas is primarily attributable to an increased frequency or magnitude of natural hydrological phenomena.

In other regions, particularly in France, approximately 18,000 municipalities (Garry et al., 2002) have already experienced this phenomenon, reflecting the significance given to this risk by public authorities. Over the past few decades, floods have led to considerable damages, with average annual costs estimated at €611 million for the period 1980-2000 (Gresillon, 2004). This rise in damages is mainly attributed to the urbanization and industrialization of flood-

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prone areas (Torterotot, 1993), which has increased the vulnerability of both properties and people.

Firstly, according to Laganier and Scarwell (2003), the increase in exposure, asset value, and frequency of extreme events intensifies the impacts of these hazards on societies. Furthermore, it appears that resignation towards natural disasters is decreasing within modern societies, as evidenced by the growing rationalization of risk observed in industrialized societies (Beck, 2001). Alcántara-Ayala (2002) notes that although the global population increased during the second half of the 20th century, the number of deaths from natural disasters remained constant, which can be attributed to a reduction in vulnerability and improvement in flood forecasting.

Regarding studies in hydrogeomorphological mapping, they reveal several advantages of this method, such as reduced cost, quick execution, and better visibility of flood-prone areas (Masson et al., 1996). This approach has proven effective in mapping extreme floods, as evidenced by analyses of events on the Ouvèze in 1992, the Aude in 1999, and the Gardons in 2002 (Masson, 1993; Chave, 2003; Garry et al., 2002; Ballais, 2006). Furthermore, the 2004 circular (METLTM et MEDD, 2004) mandates the integration of hydrogeomorphology into the Flood Risk Prevention Plans of departments in the Mediterranean region.

In Morocco, floods have become a major issue, particularly since the 1990s, with the increasing urbanization of high-risk areas. These disasters have resulted in significant damages, affecting infrastructure, residences, and agricultural lands, often accompanied by human losses during flash floods. Infrastructure breaches, damage to communication routes, and overload of drainage systems have been observed during major floods, notably in the Ourika valley in 1995, as well as during the floods of 2002 and 2010 in Mohammadia, El Jadida, and Casablanca, and more recently in 2014 in southern Morocco (SEEE, 2009).

The region of Taza has been the site of devastating floods triggered by several wadis crossing the urban perimeter of the city. These incidents have occurred in recent years, notably in 2000, 2002, and 2010, causing human losses and considerable material damage (Layan, 2014).

Floods in the Oued Lahdar basin region are characterized by much more intense intensity and geographical concentration than the major floods observed in the surrounding plains. The expansion of urbanization in flood-prone areas significantly exacerbates the risks and damages associated with these events. Despite the tragedies they cause, floods are quickly relegated to the background, both by local residents and urban planners, in favor of the growing concern related to drought, which affects the country more frequently and with more severe economic and social consequences. An assessment of the current situation has raised awareness of the challenges posed by Oued Lahdar floods.

Traditional flood management approaches, which may be based on statistical methods, have limitations due to the large interannual variability in watershed functioning (such as precipitation, temperature, flow, etc.). They do not fully meet the needs of safety and preservation of natural ecosystems in terms of impact reduction.

Today, in response to requests from governmental authorities, the hydrogeomorphological approach is emerging as a new technical tool for flood risk management. It allows for the identification of flood-prone areas and facilitates decision-making. This method is based on two essential principles: precaution and protection. In our study, we outline the theoretical foundations of the hydrogeomorphological approach and explain its functioning. Additionally, we illustrate its practical application through a case study of the Oued Lahdar watershed.

Introduced in 2014 by Montane, the hydrogeomorphological mapping method focuses on mapping flood-prone areas by reconstructing the functioning of hydrological systems. It analyzes riverbeds within alluvial plains, drawing on established theoretical frameworks such as Schumm's (1977) concept of river systems, Nanson and Croke's (1992) typology of alluvial plains, and Jean Tricart's 1960 classifications of riverbeds.

This approach provides qualitative information and does not directly indicate water levels and flow velocities. However, it enables the rapid generation of precise and consistent mapping across the entire treated area, considering the natural dynamics of flow and the area's history. The only drawback of this approach is that the provided boundaries only account for overflow flooding and exclude flooding from groundwater rise (Ballais et al., 2005).

The study area encompasses the eastern part of the Oued Inaouène watershed, one of the main tributaries of the Oued Sebou basin. It covers an area of 611.44 km² with a perimeter of 142.21 km, representing 11.81% of the Inaouène basin (Fig. 1). Positioned between the meridians (4°15’W; 3°58’W) and the parallels (34°34’N; 34°13’N), the Oued Lahdar watershed is bounded to the East and South by the tributaries of Oued Larbaâ, to the West by Oued Leben, and to the North by the headwaters of Oued Ouergha. This basin is traversed by a significant road network, including regional road RR N 508, which connects several villages north of Taza, such as Meknassa al Gharbiya, Had Msila, El Gouzate, and Taineste, along with a series of provincial roads linking various rural communities.

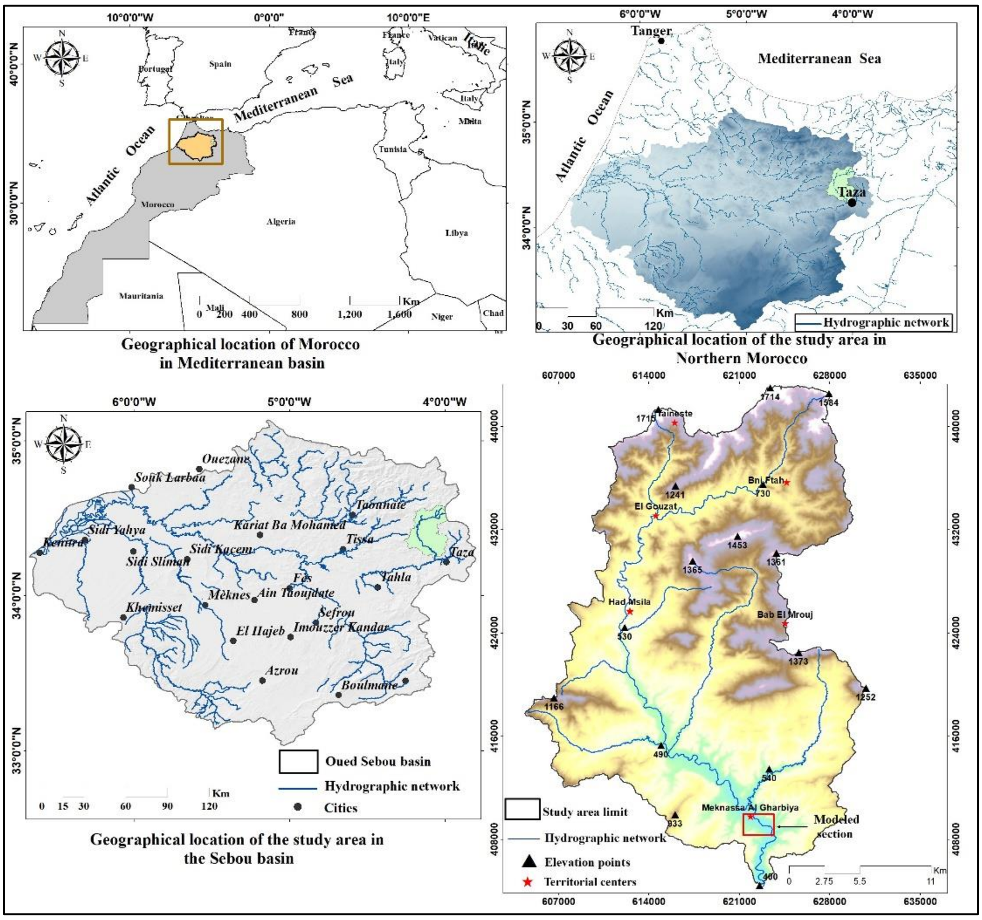

Figure 1. Location of the study area in the Oued Lahdar watershed

The watershed of the Oued Lahdar is located in the Rif Mountain range, an integral part of the system of Alpine chains of the Western Mediterranean. It extends eastward to the Algerian Tell, thus forming the Maghreb mountains.

The rock composition of the watershed is primarily made up of soft rocks, notably marls and marly limestones, which promote surface water runoff during periods of rainfall.

The topography of the watershed, characterized by low-altitude mountains and steep slopes, creates conditions conducive to rapid surface water movement from high to low. This flow dynamics result in significant sediment-laden floods.

The climate within the perimeter of the Oued Lahdar watershed is of the Mediterranean type and falls within the semi-arid category. Precipitation analysis reveals significant temporal irregularity in the watershed, regardless of the timeframe considered, ranging from daily to yearly variations, to the alternation of dry and wet periods occurring over several decades. Maximum 24-hour precipitation values are notably high, even for low return periods. These intense rainfall events can occur almost every month of the year. This underscores the susceptibility of the Oued Lahdar watershed to generating high-volume floods over short periods.

While the spatial variability of annual precipitation values within the watershed is influenced by its topography, this variability is not reflected in basin-scale values, as they are oriented similarly with respect to the precipitation source fluxes.

The spatial organization of hydrographic networks within the watershed naturally influences flow behavior, particularly in the generation of floods in main hydrographic arteries. Additionally, the slope of the hydrographic network profile plays a significant role in triggering flushing processes.

The vegetation cover is characterized by high density in the northern zone of the watershed. Conversely, it is moderate to absent towards the central and southern parts of the basin. Such distribution confirms the impact of orographic factors on climatic distribution within the Oued Lahdar watershed.

The Flood-Prone Hydrogeomorphological Units and Identification Criteria in the Watershed of the Oued Lahdar

The observation of the alluvial plain morphology has often served as the starting point for interpretation. The geomorphologist's perspective is crucial for identifying flat areas and slope breaks; the latter signify changes in units, as well as horizontal and subhorizontal surfaces characteristic of alluvial formations (Derruau, 1974; Masson et al., 1996; Nanson & Croke, 1992). Channels are spatial units delimited by continuous banks and constitute the flow paths of water. They are hierarchically organized based on the discharge they convey, from low flow to exceptional flood events (Ballais et al., 2009).

The Channel

The low-flow channel or the low-flow bed of the Oued Lahdar divides into multiple channels, separated by bars through which water flows. The course of these channels, their locations, and their morphologies change after each flood.

The Beds

The term "bed" refers to any space occupied, permanently or temporarily, by a watercourse. Their characteristics provide a sort of synthesis of the regional geomorphological evolution. Studying them should form the basis of any attempt at management, whether for flow regulation or flood control. Hence, they offer crucial importance. We typically distinguish between the major bed (ordinary and exceptional), the middle bed, and the minor bed (Ballais et al., 2009). It is important, first of all, to emphasize that the study of river beds can and should be approached from two different perspectives: the hydrological viewpoint and the geomorphological viewpoint (Ballais et al., 2009).

Low flow bed (L1)

The Low flow bed is a distinct fluvial space, characterized by the coarse grain size of its bed and its boundaries in the form of often sub-vertical and well-defined banks (Masson et al., 1996). The flow is relatively fast, and the capacity is strong, capable of transporting coarse particles such as pebbles (Photo 1).

Photo 1. Deposits of the low flow bed of the Oued Lahdar at Meknassa El Gharbiya

It can also consist of fine elements depending on the geological nature through which the watercourse passes. Indeed, the low flow bed of the Oued Lahdar upstream is characterized by the absence of pebbles, except locally in the form of pebbles a few centimeters long (fraction greater than 2mm), and by the predominance of clays and silts.

Intermediate flow channel (L2)

The intermediate flow channel, marking the transition between the low flow bed and the major bed, is characterized by its position at an intermediate altitude. These geomorphological structures are generally observed in areas where the rainfall regime exhibits strong contrasts, as noted by Delorme-Laurent in 2007. These regions often include Mediterranean areas and typically occur in sectors where rivers change course or characteristics. The topography of the intermediate flow channel is marked by a series of channels and accumulations of coarse sediments, phenomena generated by powerful currents. These surfaces can be submerged by floods with a frequency ranging from one to ten years, as reported by Masson and colleagues in 1996. The dominant vegetation in these intermediate flow channels is dense riparian vegetation, illustrating land use relatively undisturbed by human activities, likely due to frequent flooding and the strength of water flows characteristic of these areas.

The intermediate flow channel is a fluvial space located near the low flow bed, frequently occupied by medium and high water levels. It is a discontinuous flat area, as it cannot be followed along the entire watercourse. Its surface is very narrow and degraded after each flood.

Photo 2. Deposits of the intermediate flow channel at Meknassa El Gharbiya

However, it is worth noting that the grain size composition of this unit also greatly depends on what the substrate can provide.

Floodplain

Hydrogeomorphological mapping primarily focuses on distinguishing between the floodplain of a watercourse and the surrounding terrain. According to studies conducted by Masson et al. (1996) and Nanson and Croke (1992), the floodplain is described as a generally flat area located in close proximity to the watercourse. To establish this boundary, the geomorphologist follows several important methodological steps.

Firstly, the specialist works to exclude potentially flood-prone areas that do not explicitly correspond to the definition of the floodplain. This notably includes slopes that, due to their higher altitude and steep inclination, clearly stand out from the floodplain. The analysis then turns to the watercourse channel. Through lateral observations, the geomorphologist examines the relationship between the floodplain and the low flow bed or the intermediate flow channel, depending on the hydrodynamic activity of the watercourse. The demarcation of the flood zone is identified where an initial change in slope is observed laterally, with the sharpness of this change varying according to the characteristics of the physical environment.

To confirm the accuracy of this boundary, it is essential to compare it with the flood zones of upstream and downstream sections of the watercourse. The data obtained from these geometric observations are complemented by observations on current land use, allowing for further refinement of the mapping of the studied area.

The major bed or floodplain is the entire area that the watercourse floods and can cover with modern alluvial deposits indicated on geological maps. It is occupied after floods by exclusively fine sediments. These materials constitute the overflow silt (Derruau. 1986).

Ordinary floodplain (L3)

This floodplain features a horizontal or sub-horizontal surface separated from other beds of the floodplain by a bank. The ordinary floodplain is inundated by the least frequent floods. The water depth is less significant than during the inundation of the intermediate flow channel and the low flow bed (Ballais, 2007); this explains the deposition of fine elements (silts, clays) and the presence of light and fertile soils on their flats. Land use is characterized by the presence of non-hydrophilic vegetation and often marked by human presence.

Photo 3. Fine deposits from a flood in the floodplain at Meknassa El Gharbiya

Finally, these fine deposits of the floodplain often have dark colors, attributed to the richness in organic matter and reduction phenomena, whereas the surrounding material, better oxygenated, is characterized by lighter, ochre deposits.

Exceptional floodplain (L4)

The exceptional floodplain is a form that was recognized and described very recently for the first time (Chave, 2002). The exceptional floodplain (L4) is less inundated than the ordinary floodplain. The L4 is submerged at irregular intervals, but in any case, by definition, not every year (more than 50 years), so the vegetation encounters conditions that favor the development of plants less resistant to submersion, and the vegetation formations are little different from those of the interfluves (Tricat J. 1949). The alluvium that constitutes the top of the exceptional floodplains closely resembles that occupying the same position in ordinary floodplains. Despite their recent discovery and small number, they are beginning to be well understood (Aimon, 2003; Chave 2003; Delorme-Laurent, 2007; Ballais, 2009).

Methodology

The hydrogeomorphological approach is applied to valleys and alluvial plains, making it a naturalistic approach that aligns with the recent evolution of fluvial geomorphology (Ballais et al., 2009). Validated since 1996 by ministries responsible for flood hazard prevention (Masson et al., 1996), it stands within the long tradition of studying fluvial hydrosystems initiated by Davis (1899), further developed by Leopol et al. (1964) (in Ballais et al., 2009). However, it distinguishes itself from these predecessors by focusing on the risk issue that conditions its application. Its aim is not a theoretical understanding of river functioning, but rather the delineation of the maximum flood-prone area along watercourses. The hydrogeomorphological approach, on the other hand, allows for the rapid production of precise and consistent mapping across the entire treated area. It considers the natural dynamics of flow and the sector's history. This notably helps to overcome the shortcomings of hydrological statistical series and to highlight the evolving trends of rivers and associated alluvial plains. For instance, it can reveal over-sedimentation, which raises the level of the alluvial floor and consequently leads to an expansion of the floodplain, or conversely, the tendency for the river channel to incise.

The hydrogeomorphological method involves visually examining aerial photos and satellite images to analyze the terrain. These observations are then validated and enhanced through field surveys.

Photo-interpretation

The analysis of satellite images and reconstructions of the studied sections enables a reconstruction of the sensation of relief (Masson, 1983; Garry, 1985). This provides a more efficient overall view than that resulting from fieldwork by correlating indices belonging to the same parameter but often partially obscured. Analyzing all the images through geographic information systems allows for the graphical representation of various landscape elements on a map background. Aerial photographs and satellite images acquired during floods are highly relevant for flood risk mapping. Firstly, they provide qualitative information regarding flood conditions in the affected areas and can be very useful for crisis management. Secondly, these data provide access to instantaneous but spatially distributed information concerning flooded areas and water levels propagated by cross-referencing with topographical data.

Field observations

The conventional method for creating hydrogeomorphological maps relies on a two-step process: photo-interpretation, followed by field validations by specialists. This process is detailed in various methodological guides, such as those by Ballais et al. (2011), DIREN PACA (2007), and Masson et al. (1996), which describe the necessary steps for precise and effective hydrogeomorphological mapping.

The initial phase involves creating a hydrogeomorphological map on paper using data gathered during aerial image analysis, also known as photo-interpretation. These maps are crucial during field visits, not only allowing for new observations to be recorded but also enabling adjustments directly on the map. This approach facilitates practical interaction with geographic data during fieldwork. Additionally, systematic field analysis complements the photo-interpretation process by validating and refining the information obtained, particularly in cases where vegetation is dense, or boundaries are poorly defined.

Historical data

Hydrogeomorphological mapping, known for its naturalistic approach, places great importance on historical flood data. These data are crucial as they lend legitimacy to interpretations in this field, as noted by Montagne (2014). Moreover, a major advantage of this mapping method, often highlighted in various academic studies, lies in its particular utility for rivers and watercourses lacking detailed historical flood data. Authors such as Ballais et al. (2011) and Masson et al. (1996) have emphasized the hydrogeomorphological mapping's ability to serve as a valuable complementary resource, providing essential information where historical archives are lacking.

Historical flood records are highly relevant for mapping flood-prone areas. Such data can be collected either through field surveys by interviewing local residents who have experienced past events or by revisiting archives and historical texts. These data can provide valuable clues for spatially mapping flooded areas, complementing traces of past floods. Baker (1976) goes further in his interpretation by directly linking the geomorphology of floodplains to historical floods. All of this allows for connecting the past with the present when observing current land deformations that testify to the violence of past events. These data are analyzed to verify the validity of information through cross-referencing different sources. These landmarks can be supplemented by new surveys conducted during field visits and inquiries with local authorities and residents. This work refines hydrogeomorphological mapping while synthesizing past events. Indeed, historical data retain a value far superior to any statistical flood analysis or hydrogeomorphological mapping when it comes to flood risk management (Lang et al., 2013).

Results

The contribution of the hydrogeomorphological approach primarily lies in delineating the active alluvial plain covering the maximum flood expansion boundaries (Nejjari & EL Ghachi, 2016). Due to the extensive nature of the alluvial plain of the Oued Lahdar, we will present the mapping of only three sections of the valley, representing three representative sheets of the entire watershed: upstream, midstream, and downstream of the watershed (Fig. 1, Fig. 2).

The flood zone maps presented were created using the hydrogeomorphological method. The defined boundaries were further supported by field observations and the results of investigations into historical floods.

The flood zones thus delineated result from the synthesis of historical, hydrogeomorphological investigations, and testimonies from local residents. These maps are drawn on a topographic base map (1/25,000 scale).

Hydrogeomorphological Mapping Downstream of the Oued Lahdar Watershed

Geomorphologists must pay particular attention to the precise identification of flood zone boundaries when creating hydrogeomorphological maps. This information is essential because it defines regions where the risk of flooding is highest and thus requires specific monitoring and management measures.

The hydrogeomorphological maps of the flood-prone areas of the Oued Lahdar in the downstream section were carried out on the stretch near the Meknassa El Gharbiya Center (Fig. 2 and Fig. 3). Although this center is far from the channel of the Oued, it is relatively threatened by floods. The exceptional floodplain on the right bank has an opening that allows floodwaters to reach the ends of the Center.

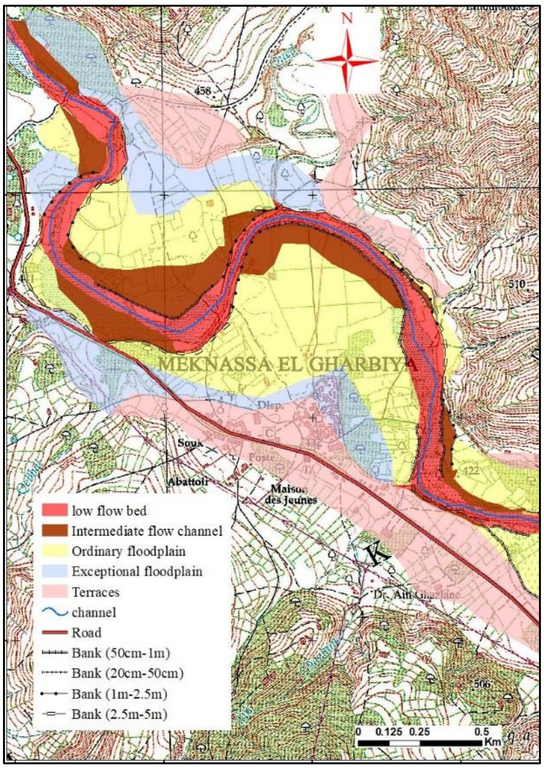

Figure 2. Hydrogeomorphological mapping of the beds in the alluvial plain of the Oued Lahdar (section 1, Meknassa El Gharbiya Center downstream of the watershed)

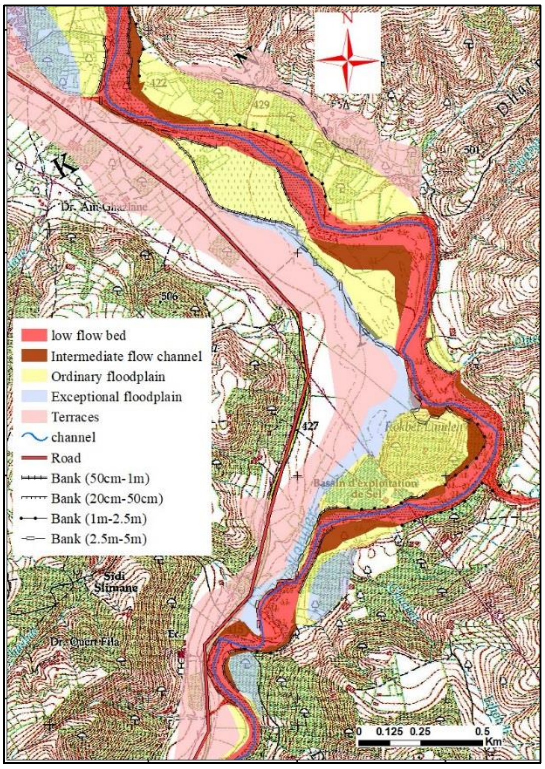

Figure 3. Hydrogeomorphological mapping of the beds in the alluvial plain of the Oued Lahdar (section 2, Meknassa El Gharbiya Center downstream of the watershed)

The results generated by the hydrogeomorphological analysis provide a comprehensive and consistent view of the flood fields across the entire section of Meknassa El Gharbiya, highlighting at a primary level the most vulnerable areas in terms of existing buildings and infrastructure. However, the information provided remains essentially qualitative, even if supplemented, where available, by historical data.

Hazard Maps

The intersection of information from the hydrogeomorphological analysis with historical testimonial data often reinforces the boundaries of the flood-prone zone. Historical information collected on the watershed is only partial. It describes areas where significant damage occurred, including flooded roads, houses, or severe weather events. By examining historical events on a larger scale, the flood-prone zone defined using the hydrogeomorphological method may lie outside the flooded area for recognized floods.

Using the spatial analysis capabilities of integrated data in the Geographic Information System (ArcGIS), we created the final map by overlaying historical results with the results of the hydrogeomorphological method. Through this process, we have produced an indicative hazard map for the Oued Lahdar watershed.

The delineation of flood hazard in the Oued Lahdar watershed is carried out using satellite imagery as a support.

The risk levels generally align with those defined for the overlay of results from the hydrogeomorphological approach and hydraulic modeling, particularly in terms of qualification:

- Low risk (exceptional floodplain): Low degree and low to medium occurrence.

- Moderate risk (ordinary floodplain): Medium degree and low to medium occurrence.
- High risk (intermediate flow channel): High degree (or high occurrence).
- Very high risk (low flow bed): Very high degree.

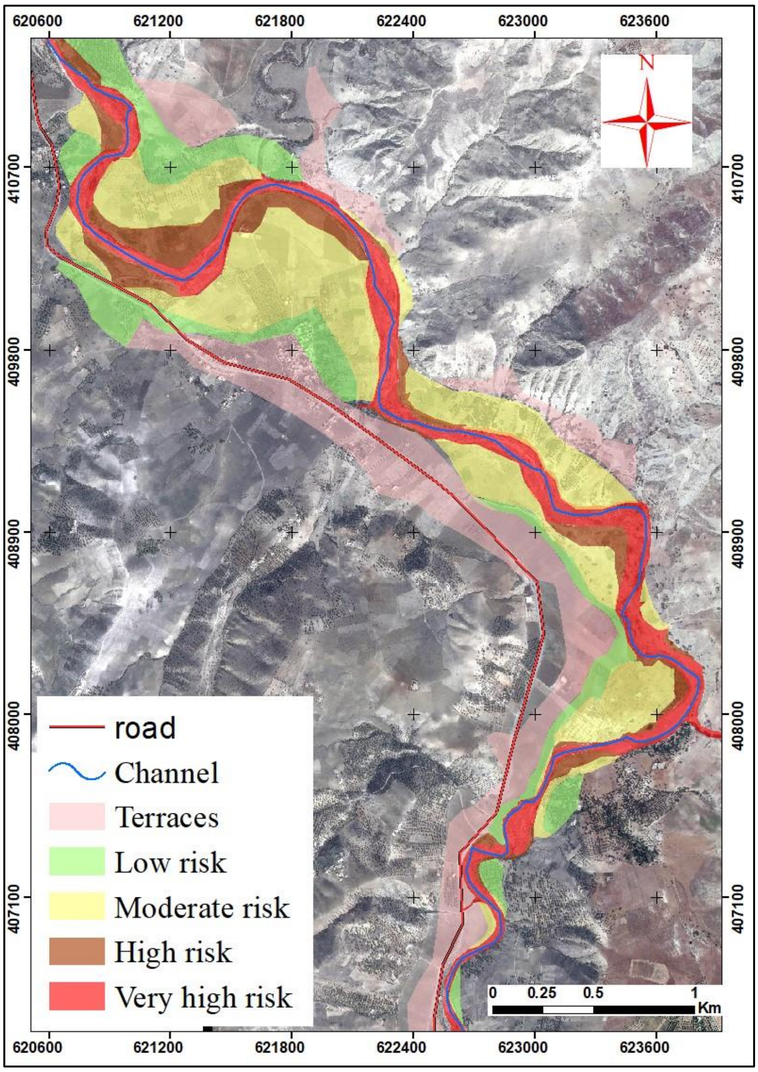

Figure 4. Flood risk zoning map of the Oued Lahdar at the Meknassa El Gharbiya Center in the downstream sector of the watershed

Discussion

This section is characterized by a flat and wide alluvial plain, bounded by a gently sloping bank on the right bank and vertical banks on the left bank. The slope is low, and the channel is sinuous and meandering. However, flood-prone areas extend across the entire width of the right bank. The predominantly marly geology in this sector and the presence of anthropogenic activities, which obstruct the flow of the river and somewhat enclose the landscape of the valley, are responsible for a bed that remains constantly wet and in connection with the Oued, whose floodwaters can spread here. Civil and industrial engineering structures (canals, roads, multiple crossing structures, etc.) undoubtedly promote water retention, and therefore anthropogenic activities considerably alter the nature and intensity of responses in fluvial systems. Locating these structures is an essential step for a rigorous delineation of the different levels of hazards (very high, high, moderate, and low), thus incorporating the effects of developments.

The valley of the Oued Lahdar in this part is wide, and the extent of flooded areas is relatively large. In areas where the morphology of the watercourse meander is not or minimally visible, we relied on historical flood mapping as well as discussions on habitats to determine the extent of the major floodplains. The information from the hydrogeomorphological analysis (photo-interpretation + fieldwork) is transposed onto the topographic map at a scale of 1:25,000.

The delineation of the intermediate flow channel within this section is sensitive. The intermediate flow channel results from the overflow of relatively frequent floods, occurring every few decades to every twenty years, or even less frequently, when significant hydraulic developments occur, such as modifications of natural flow patterns through channel realignments. Hydrodynamically, this space generally corresponds to the historical mobility zone of the watercourse, that is, the area where the low flow bed can migrate. The erosive risk due to high-flow events is high in this area.

The floodplains represent highly valued areas for human societies, primarily due to two attractive characteristics: firstly, the exceptional fertility of their soils, which favors agriculture, and secondly, their flat topography, which greatly facilitates urban development and planning. Consequently, these areas accumulate a large portion of economic, cultural, and social activities and values in flood-prone regions, underscoring their strategic importance despite the associated risks (Ballais et al., 2011; Masson et al., 1996).

Furthermore, the way human societies have developed their territories provides many useful insights. For example, the age of buildings is a crucial consideration. Generally, older buildings are situated outside the flood-prone zone, while many recent constructions are frequently located within flood-prone areas.

The granulometric and morphological analyses have demonstrated that this surface represents the exceptional floodplain. Transversely, this exceptional floodplain is not preceded by an ordinary floodplain. However, longitudinally, upstream as well as downstream, it is effectively separated from an ordinary floodplain by a bank of less than one meter, justifying that this surface should be attributed to the exceptional floodplain.

Due to the unclear external boundaries of the flood-prone zone, it is difficult to finely identify the extent of the alluvial floor. The respective widths of the minor, intermediate, and major beds visibly vary along a watershed valley. Generally, the intermediate-major bed ensemble extends much wider than the minor bed. Furthermore, the nesting of the different beds can occur in several ways. Generally, the river's shift from one bank to the other by forming a meander produces asymmetry in the floodplain, with alternation of major bed extensions from one bank to the other. This organization of the floodplain is strongly conditioned by the lithology and structure of the substrate.

The map (Fig.4) obtained covers the two representative sheets of the entire Center. The four degrees of flood dangers (very high, high, moderate, and low) are represented by the colors red, orange, yellow, and green, respectively. Each color recommends a particular type of measures to be taken to reduce vulnerability.

The red color represents areas where events of very high intensity are likely to cause loss of human lives and significant property damage. In these zones, a formal prohibition of construction should be enforced, and structural protective measures should be implemented for existing buildings and all socio-economic infrastructures located in high-risk areas with high vulnerability.

The orange color represents areas affected by events of high intensity but with a high or moderate probability of occurrence. Loss of human lives is not expected, but significant material damage is possible. In these zones, new constructions should be subject to various vulnerability reduction measures. Awareness-raising and information campaigns for residents should also be planned in these areas.

The yellow color represents areas where events of moderate intensity and probability of occurrence can cause minor damage. Awareness-raising among residents is the main measure to be taken in this zone.

The green color represents areas with very low flood risk, where inundation events are very rare. This degree is assigned to agricultural lands and cultivated fields along the Oued, as well as fruit trees (olive, almond, and carob trees).

In general, hydrogeomorphological mapping represents a comprehensive approach. This approach is based on the marks left by floods in the river landscape. The maximum envelope of rare to exceptional floods must be thoughtfully integrated into development plans. Therefore, the adoption of a multidisciplinary approach in assessing flood recurrence and determining flood-prone areas in the Oued Lahdar watershed is necessary. Extreme events have been numerous in recent years. In the context of climate change, these events are likely to occur much more frequently. Furthermore, fluvial systems strongly respond to human alteration of the landscape, and evaluating their response solely from a statistical perspective may prove inadequate. Analyzing the Oued Lahdar valley using hydrogeomorphological mapping allows for a better understanding of the floods that have occurred and can guide the development of these municipalities in a flood risk management perspective.

Conclusion

The hydrogeomorphological mapping method is recognized for its scientific rigor in identifying and mapping flood-prone areas, as evidenced by various studies (Ballais et al., 2011; Chave, 2003; Garry et al., 2002; Masson et al., 1996). This approach is rooted in a rich intellectual tradition, stemming from fundamental studies in geomorphology (Leopold et al., 1964; Nanson & Croke, 1992; Schumm, 1977) and the development of advanced techniques in geomorphological mapping (Joly, 1962; Tricart, 1965). However, there are aspects that require further exploration.

In practical terms, the application of this method in the territorial center of Meknassa El Gharbiya has provided precise results. It has enabled the delineation of flood-prone areas along the valley in the event of exceptional floods and understanding the dynamics affecting the various identified flood beds. This work demonstrates that deepening our understanding of the specific processes governing the evolution of alluvial plains is crucial for improving flood risk assessment in a given region.

In this regard, recognizing the extent of elements of the floodplain (channel, beds: L1, L2, L3, and L4) helps determine the extent of flood-prone areas at the Meknassa El Gharbiya Centers for an exceptional flood, and identifying the dynamics exerted on the different recognized flood beds. That is, a better understanding of the processes specific to the evolution of the floodplain contributes to a better assessment of flood risks in a territory.

In the field, we have observed anthropogenic modifications affecting flow conditions. These have made it difficult to distinguish the beds that make up the floodplain because some topographic elements due to human activity may appear natural in initial field analysis (e.g., embankments, dikes, quarries, and agricultural activity...).

The map obtained using ArcGIS can be considered a basic tool for guiding decisions regarding flood hazard prevention, planning, management, and establishing reliable occupancy regulations for the studied riverine space.

Finally, hydrogeomorphological analysis allows for the delineation of the maximum flood envelope, but defining acceptable risk within this zone is more challenging. Hydraulic modeling allows for the rapid delineation of a line where frequent floods occur, which can be integrated into the delineation of the risk zone. The complementarity of the two methods leads to better flood risk management in the area.

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