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DEVELOPMENT OF A FLOOD SENSITIVITY MODEL TO IMPROVE LAND LOCATION AND URBAN PLANNING USING THE ANALYTIC HIERARCHY PROCESS (AHP) METHOD AND GEOGRAPHIC INFORMATION SYSTEM (GIS): THE RISK OF FLOODS IN THE CITY OF TEBASSA (ALGERIA) AS A MODEL

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EXTENDED ABSTRACT

Le inondazioni rappresentano uno dei fenomeni naturali più diffusi e distruttivi, in particolare nelle regioni semi-aride dove l'espansione urbana si combina con sistemi di drenaggio e pianificazione inadeguati. La città di Tébessa, situata nel nord-est dell'Algeria, è soggetta a eventi alluvionali ricorrenti (1973, 1995, 2013, 2018, 2023) che hanno causato gravi danni alle infrastrutture e alle abitazioni. Questo studio propone un quadro metodologico integrato che combina il Processo Gerarchico Analitico (AHP) e i Sistemi Informativi Geografici (GIS) per valutare, classificare e spazializzare le zone di suscettibilità alle alluvioni, con l'obiettivo di migliorare la pianificazione urbana e la gestione del rischio di disastri. L'obiettivo principale della ricerca è identificare e assegnare un peso ai fattori che influenzano maggiormente la vulnerabilità alle alluvioni, produrre una mappa spaziale della sensibilità alle inondazioni che integri variabili fisiche e socio-economiche, e proporre raccomandazioni pratiche per integrare il rischio idraulico nelle politiche di sviluppo urbano. Lo studio si basa su un approccio che utilizza dati spaziali provenienti da più fonti, includendo topografia, pendenza, densità di drenaggio, tipo di suolo, distanza dai corsi d'acqua, uso del suolo e densità di popolazione, tutti elaborati attraverso la tecnologia GIS. Ogni fattore è stato valutato e normalizzato mediante il metodo AHP per garantire una struttura di pesatura coerente, consentendo così la combinazione di informazioni qualitative e quantitative. L'area di studio comprende il comune di Tébessa, che si estende su 13.878 km², caratterizzato da un clima semi-arido con precipitazioni medie annue di circa 380 mm e un marcato rilievo montuoso circostante. La città si trova all'interno di un bacino alluvionale collassato, attraversato da oued effimeri (Rafana, Zaarour, Nagues e Segui) che presentano un comportamento torrentizio durante le piogge intense. Questa configurazione geomorfologica, unita all'espansione urbana nelle zone a rischio, rende la città altamente vulnerabile alle piene improvvise. L'approccio AHP è stato impiegato per valutare sistematicamente la rilevanza relativa dei fattori che contribuiscono al verificarsi delle inondazioni. I pesi ottenuti indicano che la pendenza (0.574), il tipo di suolo (0.229) e la densità di drenaggio (0.136) sono i parametri fisici predominanti, mentre l'uso del suolo (0.75) e la densità di popolazione (0.25) rappresentano i principali indicatori di vulnerabilità. Il rapporto di coerenza (CR=3,7%) conferma l'affidabilità dei giudizi degli esperti. Tutti gli strati tematici sono stati riclassificati, rasterizzati e integrati spazialmente in ambiente GIS per generare mappe di pericolo, vulnerabilità e rischio composito di inondazione. La mappa finale del rischio alluvionale distingue cinque classi che variano da una suscettibilità molto bassa a una molto alta. I risultati mostrano che il 32.06% dell'area di studio rientra nella categoria di alto rischio, in particolare nel nucleo urbano centrale e nei quartieri densamente edificati come Merdja, El Mraghdia, Bouhaba e la zona dell'aeroporto. Le aree a rischio medio rappresentano il 18% della superficie totale, situate principalmente nelle zone periurbane di transizione, mentre il 28% dell'area presenta livelli di pericolo basso. La mappatura della vulnerabilità rivela che il 41% dell'area, comprendente settori densamente popolati ed economicamente attivi, è classificato come altamente vulnerabile. I bacini idrografici più critici sono quelli dei oued Nagues, Zaarour, Rafana ed Esgui, che convergono verso la pianura centrale della città e spesso esondano durante precipitazioni intense. Questi risultati mettono in evidenza la discrepanza spaziale tra i modelli contemporanei di espansione urbana e le aree soggette a rischio idraulico, sottolineando la scarsa integrazione dei dati idrologici negli strumenti di pianificazione come il Piano Direttore di Assetto Urbano (PDAU) e il Piano di Occupazione del Suolo (POS). Lo studio evidenzia la necessità urgente di perfezionare le normative sull'uso del suolo, riabilitare le infrastrutture idrauliche e istituire zone verdi tampone per mitigare gli impatti delle inondazioni. Dal punto di vista metodologico, l'integrazione tra GIS e AHP dimostra un'elevata efficacia e adattabilità per la valutazione del rischio alluvionale urbano in contesti caratterizzati da scarsità di dati. Essa offre un modello replicabile che consente ai decisori di visualizzare la vulnerabilità multidimensionale e di stabilire priorità d'intervento. Oltre al suo contributo scientifico, questo studio fornisce indicazioni operative per l'integrazione della mappatura del rischio nei quadri di pianificazione territoriale in Algeria e in altri contesti mediterranei esposti a estremi idroclimatici.

Il modello proposto contribuisce allo sviluppo urbano sostenibile promuovendo decisioni basate su dati scientifici, una gestione del territorio orientata alla resilienza e un migliore coordinamento tra autorità locali, protezione civile e agenzie ambientali. In sintesi, la ricerca propone un cambiamento di prospettiva nella governance urbana, sottolineando l'importanza dell'integrazione e dell'inclusione delle informazioni sul rischio nei processi decisionali, con l'obiettivo di ridurre l'esposizione alle inondazioni e favorire lo sviluppo di ambienti urbani adattivi e resilienti.

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ABSTRACT

This study applies the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) to assess flood vulnerability in Tébessa, Algeria, considering social, physical, and resource-related factors. Between 2008 and 2023, rainfall events of 45-70 mm caused extensive flooding, impacting most urban areas, especially rapidly growing neighborhoods, and resulting in significant damage to buildings and infrastructure. Social factors were found to be the main contributors to risk exposure. High hazard zones cover 32.06% of the city, mainly in central areas and older neighborhoods, while medium and low hazard levels account for 18% and 28%, mostly in peripheral areas. The uncontrolled expansion along river corridors (Zaarour, Naqis, Rafanah, and Saqi) has increased flood risk. The combined AHP-GIS approach identifies critical zones, evaluates potential impacts, and supports management strategies, including contingency planning and land-use regulation. The resulting thematic vulnerability maps provide essential guidance for prioritizing risk areas, improving urban resilience, and implementing sustainable planning and prevention measures. By synthesizing complex spatial data into a comprehensive vulnerability index, this methodology facilitates informed decision-making, protects people and infrastructure, and strengthens flood risk management in Tébessa.

Keywords: *flood vulnerability, analytic hierarchy process (AHP), geographic information systems (GIS), urban planning, land suitability, Tébessa*

INTRODUCTION

Floods are among the most destructive natural hazards worldwide, causing severe losses to human life, the economy, and the environment. Their impacts are amplified in urban areas due to rapid and often unplanned urbanization, high population density, and increased imperviousness of surfaces, which reduces infiltration and increases surface runoff (Rahmati *et alii*, 2016; Lyu & Yin, 2023). In developing countries, these effects are exacerbated further by weak institutional mechanisms, fragmented governance, and the absence of integrated planning and prevention strategies (UNDRR, 2022). Like many Mediterranean countries, Algeria is increasingly exposed to extreme hydro-meteorological events, particularly in medium-sized cities, where predictive and preventive systems are underdeveloped (Khentouche & Bella, 2025; Gherabi *et alii*, 2024). Historical disasters, such as the Bab El Oued flood in 2001 and the Oued R'Hiou event in 1993, have caused hundreds of fatalities and revealed the structural weaknesses of existing risk management frameworks (Chellali, 2018). These events underscore the urgent need to integrate flood risk assessment and mitigation into spatial planning and urban development strategies. Flood risk is commonly defined as the combination of hazard, exposure, and vulnerability (UNISDR, 2015; Versace *et alii*, 2023). Assessing flood risk requires understanding both natural and human-induced factors. Although traditional hydrological and hydraulic models have long been used to simulate flood behavior, they are often data-intensive and ill-suited to regions with limited data availability, such as semi-arid environments. Consequently, integrating Geographic Information Systems (GIS) with Multi-Criteria Decision-Making (MCDM) methods, especially the Analytic Hierarchy Process (AHP), has emerged as a powerful alternative for evaluating and mapping flood risk. GIS allows for the efficient integration, analysis, and visualization of spatial data, and the AHP provides a systematic framework for weighing and prioritizing factors based on expert judgment (Saaty, 1980; Das, 2019).

The hybrid GIS-AHP approach is increasingly being applied worldwide due to its efficiency, flexibility, and transparency when handling complex spatial issues related to natural hazards and urban planning. Numerous studies have demonstrated its robustness and adaptability in various geographic and climatic contexts. For example, Elmahdy and Mohamed (2020) used GIS-AHP to identify flood-prone areas in Egypt's arid regions, while Aichi *et alii* (2024) validated its performance in Morocco's semi-arid Wadi Dades watershed. Arca and Yalcin (2023) introduced a fuzzy-AHP variant in Turkey to address uncertainty in expert evaluations, and Essahlaoui *et alii* (2025) expanded the method to include morphological and hydrological parameters in Morocco's Meknes region. Kafando *et alii* (2023) demonstrated the model's effectiveness in Ouagadougou, Burkina Faso, and Nguyen *et alii* (2024) and Singh *et alii* (2024) confirmed its relevance for urban flood management in Hanoi, Vietnam, and the Philippines, respectively. Together, these studies emphasize the worldwide acceptance of GIS-AHP as a dependable tool for assessing flood susceptibility, particularly in regions with limited data and rapid urbanization. However, limited research has focused on medium-sized, semi-arid cities, such as Tébessa in northeastern Algeria. There, complex topography, informal urbanization, and scarce hydrological data create specific analytical challenges. The city's semi-arid climate and intricate drainage network of ephemeral oueds connected to Oued Kébir make it highly susceptible to flash floods triggered by short-duration, high-intensity rainfall. The lack of hydrological considerations in urban planning, insufficient drainage infrastructure, and the proliferation of informal settlements in flood-prone zones have led to recurring flood events in 1973, 1995, 2013, 2018, and 2023. These events have caused property damage and social disruption (Talbi *et alii*, 2023). The Urban Master Plan (PDAU, 2012) and executive decrees promoting new urban poles (No. 11-237 and 11-239, 2011) aimed to structure urban growth; however, many constructions still occupy flood-prone areas (National Economic and Social Council, 2003). Addressing this situation requires a scientifically sound, spatially integrated method to support preventive urban planning and sustainable land use management. Therefore, this study aims to develop a geographic information system (GIS)-analytic hierarchy process (AHP)-based flood sensitivity model adapted to the environmental and socio-urban context of Tébessa.

The objectives are threefold: (1) to construct a multi-criteria flood vulnerability model that integrates physical, environmental, and anthropogenic factors, (2) to evaluate its effectiveness in a semi-arid urban environment, and (3) to propose spatially explicit recommendations for flood-resilient land use and sustainable urban development. This research makes an original, context-specific contribution to the scientific literature by bridging global methodological advances with local spatial realities. It demonstrates the value of GIS-AHP integration as a framework for supporting decisions about climate-resilient urban planning. To this end, the study's methodological framework integrates the Analytic Hierarchy Process (AHP) within a Geographic Information System (GIS) environment to create a spatially explicit flood sensitivity model. The conceptual approach assumes that flood susceptibility results from the interaction of physical factors (e.g., elevation, slope, drainage density, and landform), environmental parameters (e.g., land use/land cover, soil type, and vegetation), and anthropogenic elements (e.g., proximity to roads, built-up areas, and population density). Each criterion was selected based on its relevance to flood generation processes and local geomorphological characteristics. The AHP method was applied to determine the relative weights of these factors through pairwise comparisons, ensuring transparent, reproducible evaluation of their influence on flood potential. Subsequently, all weighted criteria were integrated using GIS spatial analysis tools to produce the final flood sensitivity map. This hybrid GIS-AHP framework links quantitative spatial data with expert-based reasoning, providing a robust basis for decision-making. It supports local authorities and urban planners in identifying flood-prone zones, prioritizing preventive measures, and guiding future land allocation toward more resilient and sustainable urban development.

STUDY AREA

The city of Tébessa is located in northeastern Algeria, near the Tunisian border. It serves as the administrative center of the Tébessa Wilaya. The city lies between latitudes 35°24′ and 35°26′ N and longitudes 8°06′ and 8°09′ E, covering an area of approximately 14 hectares (Fig. 1). The region has a semi-arid climate, with hot, dry summers and cold, rainy winters. Annual precipitation varies between 300 and 350 millimeters and is concentrated mainly from November to March. Situated at an altitude of approximately 850 meters above sea level and surrounded by steep hills and wadis, the city is naturally prone to rapid surface runoff during intense rainfall. The hydrographic system is composed mainly of ephemeral streams, such as Oued El-Kebir and Oued El-Hammam, which cross the urban fabric and contribute to recurrent flooding during heavy storms. Tébessa's urban growth has expanded irregularly along natural drainage paths, often without adequate planning or drainage infrastructure. This has significantly increased the vulnerability of the built environment to flooding. Over the past decade, the city of Tébessa has experienced several major flood events associated with climatic variability and rapid urbanization.

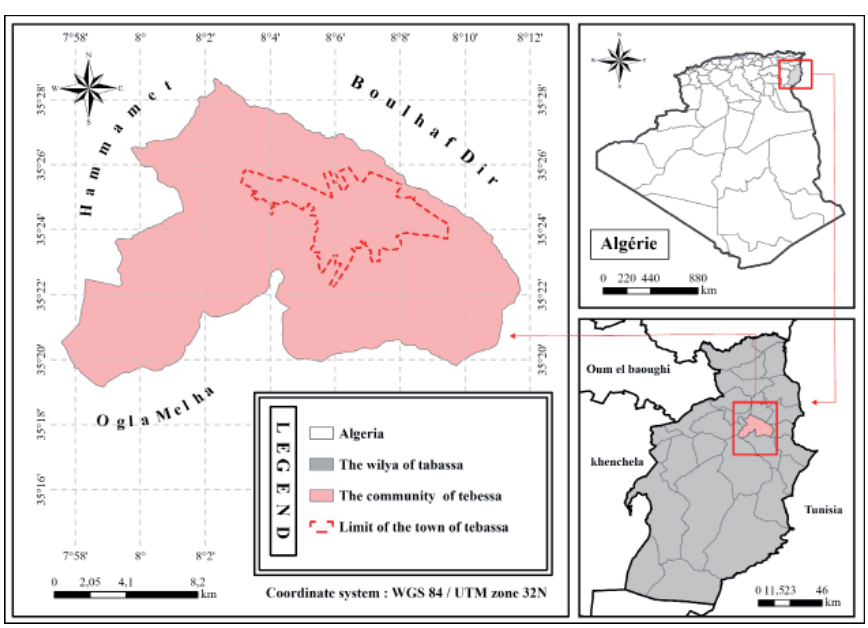

Fig. 1 - Geographical location of the municipality of Tebassa (Boussetti, 2024)

According to data from the Civil Protection Directorate (2023), between 2013 and 2022, Tébessa experienced a series of intense hydrological events requiring numerous emergency interventions, reflecting the urban system's persistent structural vulnerability. Early events between 2013 and 2015 caused material damage, such as cracks in houses, mosques, and schools. The first recorded fatalities occurred in 2015, with one death and twenty-six survivors. The period from 2016 to 2018 was particularly critical due to the increasing frequency and severity of floods. In 2016, three people died, and in 2018, there were 325 rescue operations, two deaths, and ten injuries. This period also revealed a notable spatial expansion of the affected zones. From 2019 to 2022, flooding occurred almost annually, requiring 93 to 272 interventions per year (Fig. 2). Though human losses were lower, these events continued to damage urban infrastructure and public facilities, demonstrating continuous hydrological pressure on the urban fabric. The heavy rains of August 27 and September 2, 2022, required 143 emergency operations, confirming the persistence of flood risk and the territory's growing vulnerability to climatic hazards.

The flood event of March 2023 further emphasized the fragility of the urban drainage system. Exceptional rainfall over a short period led to severe flooding in several districts, including El-Kouif and Boulhaf El-Haddad, which disrupted traffic and public services. These successive events demonstrate the recurrence of urban flooding and the combined effects of climate variability, inadequate land use planning, and insufficient stormwater management infrastructure. The chronological evolution of flood events in Tébessa underscores the urgent need for an integrated approach to risk management, combining urban planning, land use control, and climate change adaptation to bolster the city's resilience against future hydro-meteorological hazards.

Fig. 2 - Flood risk in Tebessa city. Directorate of Reconstruction, Architecture Tebessa, 25/10/2022

The sub watersheds in the area (Fig. 3) have a slightly elongated shape, a fairly strong relief, and gentle slopes with sparse vegetation

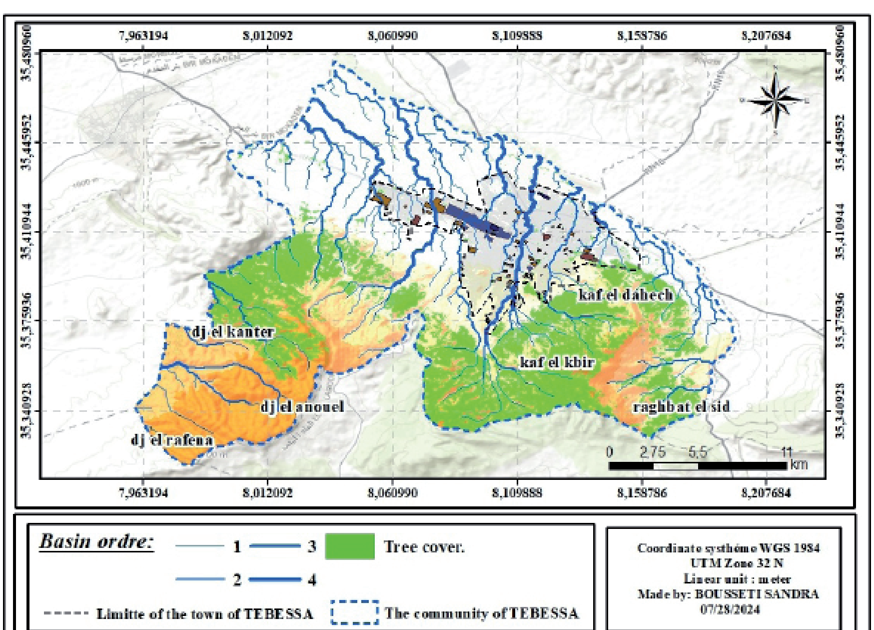

Fig. 3 - Hydrographic networks to the Municipality of Tebassa (Boussetti, 2024)

cover, which increases the effect of erosion. During the runoff, the surface waters are channeled by an extensive hydrographic network and finally flow towards the basin outlets (National Road No. 10) with flow velocities ranging from 1.15 to 2.27 m/s and a significant concentration time ranging from 0.67 hours (Chabro) to 3 hours (Rafana) (Department of Water Resources of Tebessa, 2019). The drainage density ranges from 4.12 to 5.50 km/km².

In terms of climate, Tébessa is located in a semi-arid region with mild winters. The average annual rainfall in all sub-basins is around 380 mm in 2023, and with an average temperature of 26.7°C, July is the hottest month of the year. January is the coldest month of the year with an average temperature of 6.1°C (Revision PDAU, 2018).

METHODS

Several qualitative and quantitative factors or criteria come into play when assessing the risk of flooding due to overtopping. Therefore, it is necessary to use decision support methods to facilitate the necessary choices for the evaluation. For this purpose, Saaty's Analytic Hierarchy Process (AHP) method was chosen because it allows the verification of expert judgments. The methodology used in this work generally includes the following steps (Saaty, 1995):

- Selection and development of flood risk factors or criteria;
- Application of AHP multicriteria analysis;
- Aggregation of the flood risk factors.

Input Data for Developing Flood Risk Factors or Criteria

Several methods were used to develop or map hazard factors (topography (slope), drainage density, soil types) and vulnerability factors (population density and land use) (Fig. 5). The slope was extracted from the SRTM image using Arc GIS software (or possibly QGIS) (Roukh *et alii*, 2018). The hydrographic network was also extracted from this image. The hydrographic network was then used to create the drainage density map using Arc GIS (or QGIS) software. For rainfall, satellite based rainfall data (CHIRPS data) were processed to create the isohyetal map of the region. The soil type map of the study area was digitized from an existing 1:500000 scale map of the Tebessa region (PDAU, 2018).

Slope

Slope plays a very important role in mapping flood vulnerability. This intrinsic factor controls runoff velocity and determines areas of surface water stagnation during occasional rainfall. Expressed in degrees, slope is generated from a Digital Elevation Model (DEM) and categorized into five slope classes as follows (Zitouni *et alii,* 2016; Gherzouli, 2017).

- 0-10%: The most widespread category in the region, representing mostly agricultural lands that coincide with the Marjah plain, where the Wadi el-Kebir extends, making it prone to flooding. It occupies 850 hectares, or 43% of the total area of the municipality.
- 10-12%: its presence increases towards the south, on the northern slopes of the Thala and Gouja mountains and the eastern slopes of the Tazabent plateau and Mount Qantis, covering an area of 560 hectares, or 28%.
- 12-25%: located in the southern part of the municipality at the foot of the southeastern and southwestern mountains, covering 374 hectares (18%). These areas are less suitable for development due to high construction costs and the need for technical networks, in addition to being forested. Notable areas include Hay al-Zawiya, Hay al-Zaytoun, and Hay Jebel al-Jarf.
- More than 25%: these are very steep areas unsuitable for construction and prone to erosion and landslides, including the southern, eastern, and western highlands. They are located to the south of the city and are less common than the previous categories, present in the upper areas of Hay al-Zawiya and Hay al-Zaytoun.

Based on these data, we can observe that the city of Tebessa is located in a low basin relative to the height of the surrounding mountains. This terrain morphology, surrounded by high masses, allows the appearance of fast moving water flows. In the case of intense rainfall of short or medium duration, such as that which recently occurred in this region, the water follows the slope and then causes flooding in the lowest points of the plain. Therefore, the city of Tebessa is threatened by floods due to its low position in relation to its surroundings, which is called a subsidence basin (foot of the mountain). In the southern part (the area of Larbi Tébessi University), it receives fast moving flood waters from the mountain slope (Revision of PDAU, 2018).

Topography

The territory of the municipality consists mainly of a plain-mountain duo, where the mountainous aspect dominates both in extent and in vigor. In fact, the mountains alone cover more than 50% of the territory of the commune; the massifs reach heights of more than 1500 meters and frame the Merdja plain in its southern/southeastern part. The plain itself is a west-to-east subsidence basin with an average altitude of 800 meters and its orientation follows the relief of the Tébessa mountains. This parameter plays a key role in controlling the direction of flow and the depth of inundation. The hypsometric map is generated from an automatic classification of the DEM using the ASTER DEM, which divides it into five classes (Revision of PDAU, 2018).

The Tebessa plain is part of the Medjerda River basin and the Mellégue River sub-basin. It is a subsidence basin, completely covered with alluvial materials resulting from recent movements of the bedrock. The main geological formations (Fig.

3), identified in the study area are Cretaceous, Plio-Quaternary and Quaternary. The most widespread formation in the Tebessa basin is the Quaternary, while the formations surrounding the city are mainly limestone (Gherzouli, 2017).

land: 72.094 ha; pastures and meadows: 434.116 ha; forest areas account for about 171 ha). All files were converted into a raster format with a pixel size of 30×30 meters and integrated into GIS for the application of the Analytic Hierarchy Process

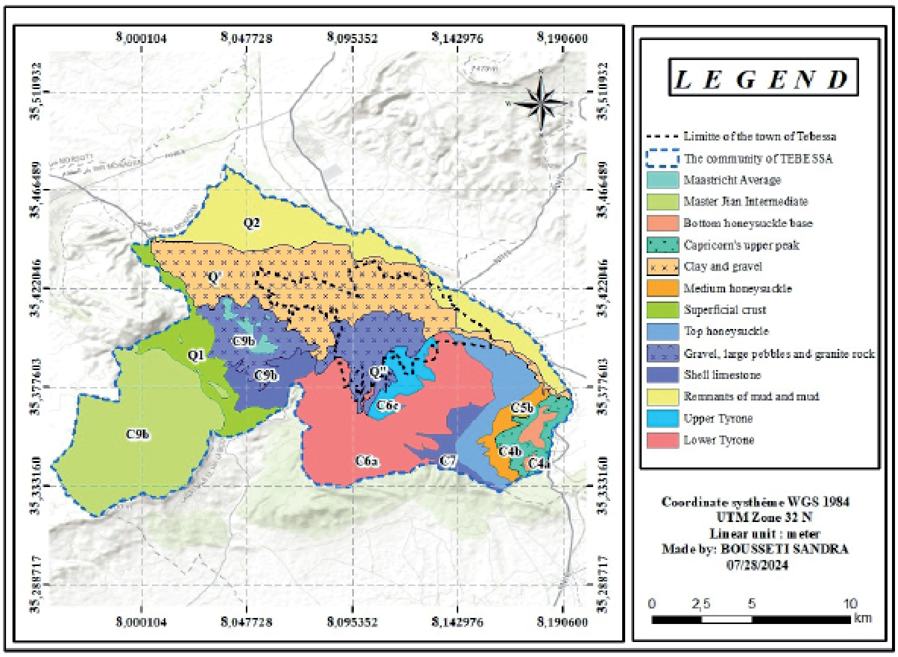

Fig. 4 - Geological map of the Municipality of Tebessa (Boussetti, 2024)

Proximity to Rivers

Areas near rivers are characterized by a high susceptibility to flooding due to overtopping. The distance from rivers is one of the most important parameters in flood hazard assessment. The watercourses in the city are ephemeral but torrential and aggressive, and this aggressiveness manifests itself in flooding within the city. The city has several rivers: Rafana, Zaarour, Nagues, Djobane, Segui, and Chabro, which is the watershed for all the aforementioned wadis. In this study, the proximity map to rivers was generated by classifying the distances from watercourses into five classes: (≥50), (50-100), (100-200), (200-400) and >400 meters (Seghir, 2008).

Land Use

Land use is also a very important parameter in zoning flood susceptibility. Bare soils, built-up areas, and zones with low vegetation density are characterized by high susceptibility to flooding. In this study, the land use map was classified into five classes according to the degree of vulnerability. According to the 2021 agricultural statistics, the agricultural sector occupies a total agricultural area of 818.357 ha, which is distributed as follows (usable agricultural area: 312.147 ha; unproductive

(AHP) method land: 72.094 ha; pastures and meadows: 434.116 ha; forest areas account for about 171 ha). All files were converted into a raster format with a pixel size of 30×30 meters and integrated into GIS for the application of the Analytic Hierarchy Process (AHP) method.

Application of Multicriteria Analysis AHP

Analytic Hierarchy Process (AHP) is a multicriteria decision making method, which helps to make correct and justified choices among multiple criteria. Introduced by this method is based on pairwise comparison of criteria (Rahmati *et alii*, 2016; Das, 2018; Ghosh *et alii*, 2018)). Due to its ease of application and accuracy in decision making, the AHP method has been used in various fields such as landslide susceptibility (Yoon *et alii*, 1995), risk management, combined transportation planning, comparative analysis of logistics operations, and flood risk assessment (Saaty, 1991).

Classification and Weighting of Criteria

The classification of the criteria is a step that involves making the factors (both qualitative and quantitative) comparable (Saaty, 1995). By constructing a square matrix, the relative importance of one factor compared to another is evaluated using

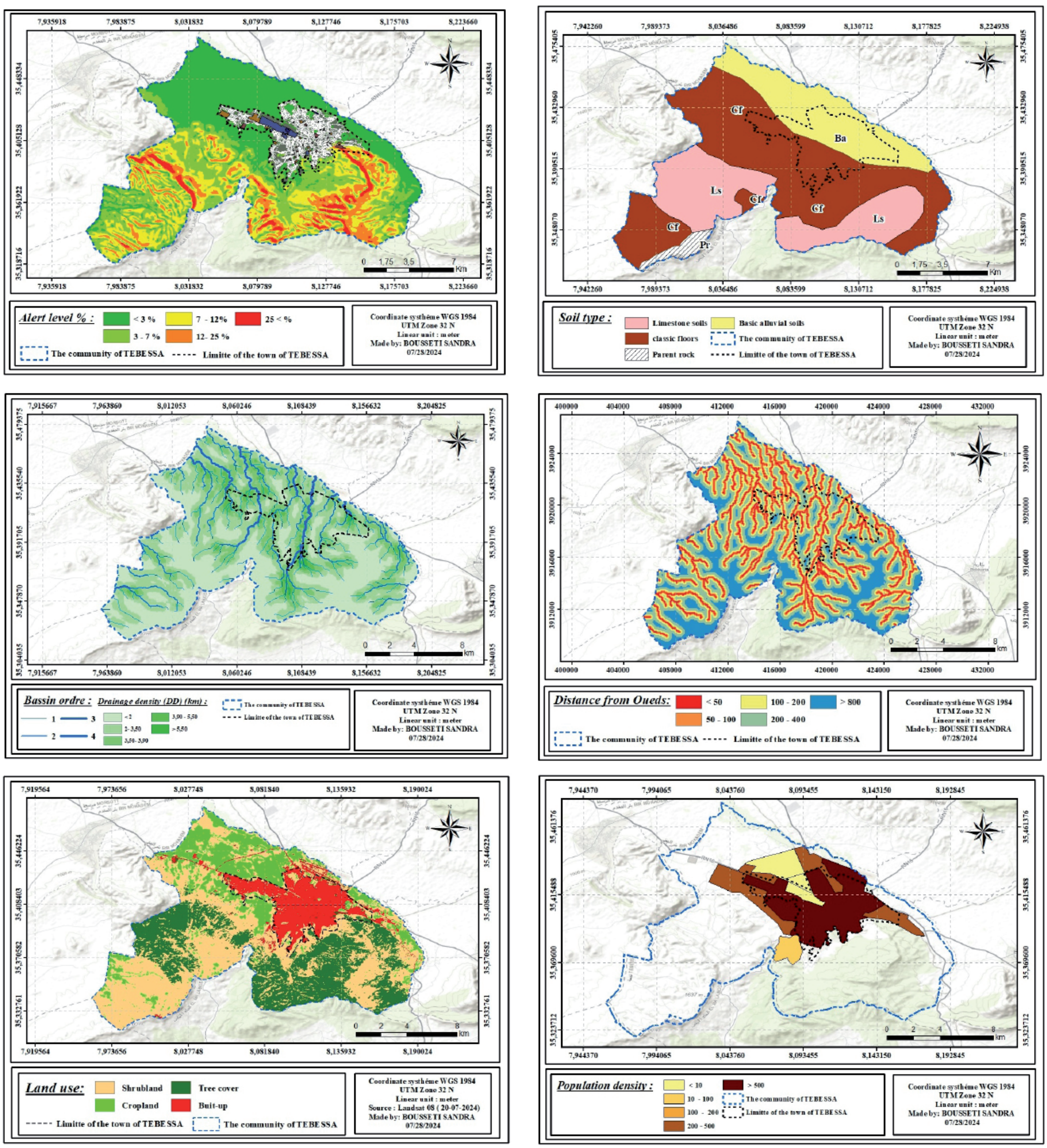

Fig. 5 - Thematic layers that have been classed, spatially processed, and employed in the study of multi-criteria land suitability based on Tebassa municipality's geographic information system: 1.Slope, 2b.Soil types,3. Drainage density, 4. Distance from West, 5. population density, 6. land use) (Boussetti, 2024)

an appropriate scale, as suggested by (Table 1).

Tables 2 and 3 show the pairwise comparison matrices of the hazard and vulnerability criteria, where the diagonal values are equal to 1. The values of each row are compared with each column to

Degree of Numerical Importance	Degree of verbal importance
1	Equal importance
3	One element is more important (sensitive) than the other
5	One element is more important (sensitive) than the other
7	One element is much more important (sensitive) than the other
9	One element is absolutely more important (sensitive) than the other
2.4.6.8	Intermediate values between two neighboring assessments
1/2.1/3.1.4.1/5.1/6.1/7.1/8.1/9	Reciprocal values of previous assessments

Tab. 1 - Fundamental scale of pairwise comparisons (Saaty, 1995)

	Slopes (P)	Soil Type (S)	Drainage Density (DD)	Distance from Oueds (DW)
Slopes (P)	1	5	7	7
Soil Type (S)	1/5	1	3	3
Drainage Density (DD)	1/7	1/3	1	3
Distance from Oueds (DW)	1/7	1/3	1/3	1

Tab. 2 - Pairwise Comparison Matrix of Hazard Criteria

	Land Use (LU)	Population Density (PD)
Land Use (LU)	1	3
Population Density (PD)	1/3	1

Tab. 3 - Pairwise Comparison Matrix of Vulnerability Criteria (V)

define the relative importance of each factor to obtain a value. We will fill the pairwise comparison matrix using the Saaty scale (1, 3, 5, 7, 9 and their reciprocals). For this example, we will use the following hypothetical judgments.

Once the comparison matrix is filled, we calculate the eigenvalue of each matrix and the corresponding eigenvector. The eigenvector (EV) or the weighting coefficient (WC) indicates the priority order of the factors studied. These parameters are calculated according to equations 1 and 2 (Saley *et alii*, 2013). They are important for the evaluation of the probability and are used to indicate the relative importance of each factor causing the flooding:

$$V_p = K\sqrt{W_1 x W_k} \quad (1)$$

k=number of compared parameters and W_k=main scores assigned to the parameters.

$$C_p = V_p / V_{p1} + \ldots + V_{pk} \quad (2)$$

The sum of the WCs of all parameters in a matrix must equal 1. This step is followed by the calculation of λ_{max}, *Ic* (Consistency Index) and *Rc* (Consistency Ratio). The calculated values of λ_{max}, *Ic* and *Rc* for the Hazard and Vulnerability Factors are recorded in Tables 4 and 5, respectively.

	Slopes (P)	Soil Type (S)	Drainage Density (DD)	Distance from West (DW)	Vp	Weight Cp
Slopes (P)	1	3	5	7	3.202	0.574
Soil Type (S)	1/3	1	2	4	1.277	0.229
Drainage Density (DD)	1/5	1/2	1	3	0.740	0.136
Distance from West (DW)	1/7	1/4	1/3	1	0.359	0.061
	K= 4	**Ia = 0.9**			**5.578**	**1**
λmax = 4.837					**Ic= 0.034**	**Rc = 0.037**

Tab. 4 - Weighting Matrix of Hazard Factors

	Land Use (LU)	Population Density (PD)	Vp	Cp Weight
Land Use (LU)	1	3	1.73	0.75
Population Density (PD)	1/3	1	0.58	0.25
	K=2	**Ia = 0**	**2.31**	**1**
λmax = 2			**Ic = 0**	**Ic = 0**

Tab. 5 - Weighting Matrix of Vulnerability Factors

When *Rc*<10%, it indicates that the experts' judgments are consistent. The calculated *Rc* is 0.037=3.7% (<10%) for hazard factors and 0 for vulnerability factors (Tab.). Therefore, the judgments for these two types of factors are considered consistent.

The pairwise comparison matrix of the hazard criteria in the urban area of Tebessa is consistent, with a Consistency Ratio (*CR*) well below the 0.10 threshold. This means that the comparative judgments of the criteria are reasonable and reliable for use in GIS for mapping flood vulnerability.

In this case, since (n=2), the matrix is automatically consistent, and we do not need to calculate the *CR*, as the *RI* for (n=2) is 0.

The linear combination of thematic layers with their respective weights is used to derive the "flood hazard due to overflow" function and vulnerability, as expressed by equation 3:

$$I=\Sigma_{j=1}^{n} \quad W_j \, w_{ij} \qquad (3)$$

With *I*: the index related to the indicator, *Wj*: the weight of parameter *j*, w_{ij}: the weight of class *i* within parameter *j*, and *n*: the number of parameters.

The "flood hazard due to overflow" function is expressed by equation 4:

OFH(Overflow Flood Hazard)=0.574x slopes+0.229 xsoil+ 0.136 Drainage Density + 0.061x Distance From West (4)

Similarly for vulnerability, it is given by the following equation 5:

V=(0.5×Land Use+0.5×Population Density) (5)

It should also be noted that one or more classes can be defined for each factor or criterion. For this study, the number of classes defined is 5. This number was determined on the basis of previous work. The weights assigned to the different classes of hazard and vulnerability criteria are recorded in Tables 6 and 7, respectively.

Indicator Qualification Criteria	Criteria	Criteria Qualifiers	Classes	Codes susceptibility	Weight (Cp)
Overflow Flood Hazard	Slope (P) in %	Very weak	<3	9	0.634
		Weak	3_7	7	
		AVERAGE	7_12	5	
		Forte	12_ 25	3	
		Strong features	>25	1	
	Soil type (S)	Weak	Parent rock	1	0.211
		AVERAGE	Limestone soils	5	
		Forte	Basic alluvial soils, sand, marl	7	
		Strong features	Calcium soils	9	0.099
	Density of drainage (DD) (km)	Very weak	< 2	1	
		Weak	2-3.50	3	
		AVERAGE	3.50-3.90	5	
		Forte	3.90-5.50	7	
		Strong features	>5.50	9	
	Distance from Oueds	Very weak	>800	1	0.057
		Weak	200-400	3	
		AVERAGE	200-100	5	
		Forte	100-50	7	
		Strong features	>50	9	

Tab. 6 - Classes of hazard criteria and their weight

Indicator Qualification Criteria	Criteria	Criteria qualifiers	Classes	Codes de Vulnérabilité	Weight (Cp)
Vulnerability	Land Use	Very weak	Bodies of water	0	0.75
		Weak	Dense forest, Outcrops/mineralized soils	1	
			Floodplain or included	5	
		AVERAGE	Degraded forest, reforestation/crops	5	
		Forte	Bare soils, degraded forests, pastures, and seasonal crops.	7	
			Housing, industrial and activity zones	9	
	Density of population	Very weak	<10	1	0.25
		Weak	10-100	3	
		AVERAGE	100-200	5	
		Forte	200-500	7	
		Strong features	>500	9	

Tab. 7 - Classes of vulnerability criteria and their weight

RESULTS AND DISCUSSIONS

The results of the pairwise comparison of the sub-criteria with respect to the criteria considered for our case study are summarized in Table 6 (the comparison matrix is standardized so that the sum of all weights is equal to 1).

Regarding the results, we have CR=0.037, so the consistency ratio is less than 0.1, which confirms that the judgments for evaluating the criteria were consistent.

Spatial analysis of hazard and vulnerability factors

In All thematic maps were created using the capabilities of Arc-GIS software, developed in a GIS environment, using a linear combination weighting method. As a result, a flood vulnerability map was obtained by classifying the vulnerability index into four potential flood classes: None, Low, Medium, and High.

The evaluated criteria are mapped in Fig. 5 using the spatial analysis capabilities of GIS. The layers with common and recorded base maps are merged based on their spatial occupancy. These results can reflect simple operations such as overlaying a road map on a wetland map to determine overlaps and co-occurrences.

Flood risk factor map (Fig. 6) presents 5 classes ranging from very low to very high vulnerability. The highest rainfall class is located far from the Tebessa collapse basin. This means that when rain falls on these mountains, the rainwater concentrates more quickly on the clayey and loamy soils of the Tébessa basin, facilitating the formation of flood-prone areas.

The hazard map (Fig. 6) shows several levels of hazard that progressively decrease from the northeast to the southwest and are presented as follows:

- the high hazard level covers 32.06% of the region. It includes most of the city center and the neighborhoods of Tebassa. The study area is composed of more than 28% of low hazard areas. The medium hazard level covers 18% of the study area outside the city.

- the vulnerability map (Fig. 7) shows five categories of vulnerability, ranging from very low to extremely high. The vulnerable areas (representing 41% of the study area) are mainly concentrated in the city of Tebassa, which has significant socio-economic characteristics (high population density and important primary and tertiary activities). The larger towns have more developed urban structures. In general, the slope of the terrain in these regions is low (<12%). The areas of low to medium vulnerability outside the study sector, which represent 20% of the study area, are actually rocky outcrops that are uninhabitable.

It is observed that the area's most vulnerable to flooding are those located at lower elevations. In addition, urbanized areas, especially the city center of Tébessa, have a particularly high vulnerability due to the significant concentration of human and material resources. The total flooded area is 26.6 km², with an average water height of 1.77 m. In terms of flow velocities, the highest are observed at the headwaters of the oueds, where the slopes are steep, while the lowest velocities are found on terrains with gentle slopes (Revision of PDAU, 2018) High relief favors water accumulation during significant floods. Due to their orientation and structure, the flood concentration time is extremely short, which allows the water to accumulate quickly in the Tébessa basin, posing a risk of flooding in various neighborhoods such as Merdja, the airport district, El Mraghdia hamlet, Bouhaba district, etc... Some areas of the city are flooded by external waters, especially in the western zone and the lower parts of the ZAAROUR, NAGUES, RAFANA and

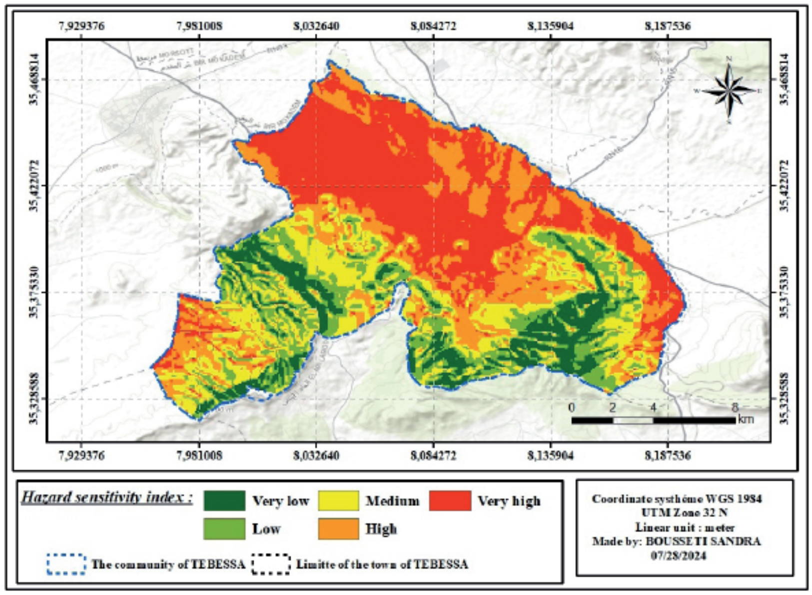

Fig. 6 - Risk of flooding in the municipality of Tebassa (Boussetti, 2024)

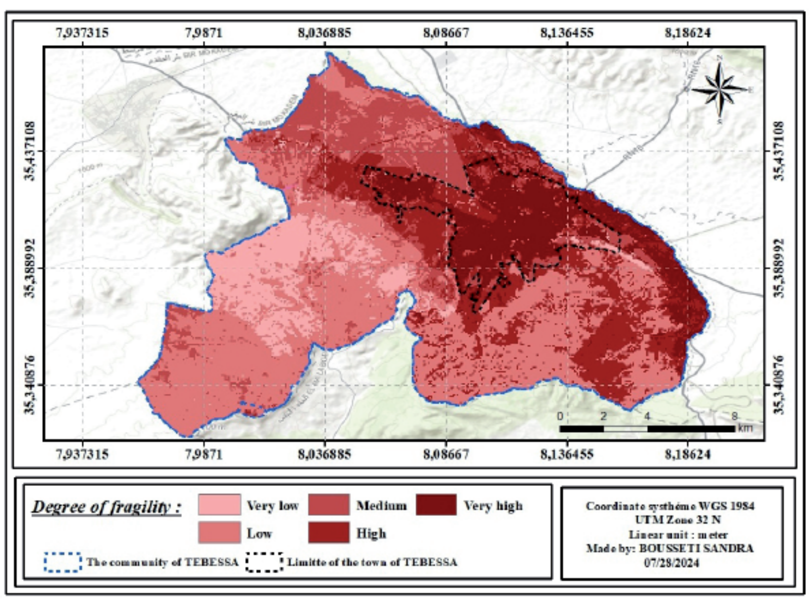

Fig. 7 - Vulnerability Map of Tebassa Municipality (Boussetti, 2024)

EL DJORF watercourses. The runoff from the catchment area of the urban zone, especially the western area, and the rising groundwater in the TAGHDA plain, which is generally not suitable for construction, also pose a threat. The torrential flow of the RAFANA, SEGUI, ZAAROUR and NAGUES streams often causes the displacement of boulders, which sometimes block the crossing structures upstream of the RN 10 (Fig. 8). Another problem is the accumulation of sediments in the alluvial fans downstream of the RN 10 after the floods have passed (Chellali, 2018).

River Nagues has been identified as the most dangerous of the catchment areas in terms of priority and risk. It is essential to take measures to mitigate the impact of its floods on the urban environment of the city. The Oued Zaarour basin follows in terms of risk, followed by the Rafana, Esgui and Razala basins (Fig. 9). Together, these watersheds pose a

Fig. 8 - *Flood Hazard of Oued EL NAGUES, Oued RAFANA (Boussetti & Marth, 2024)*

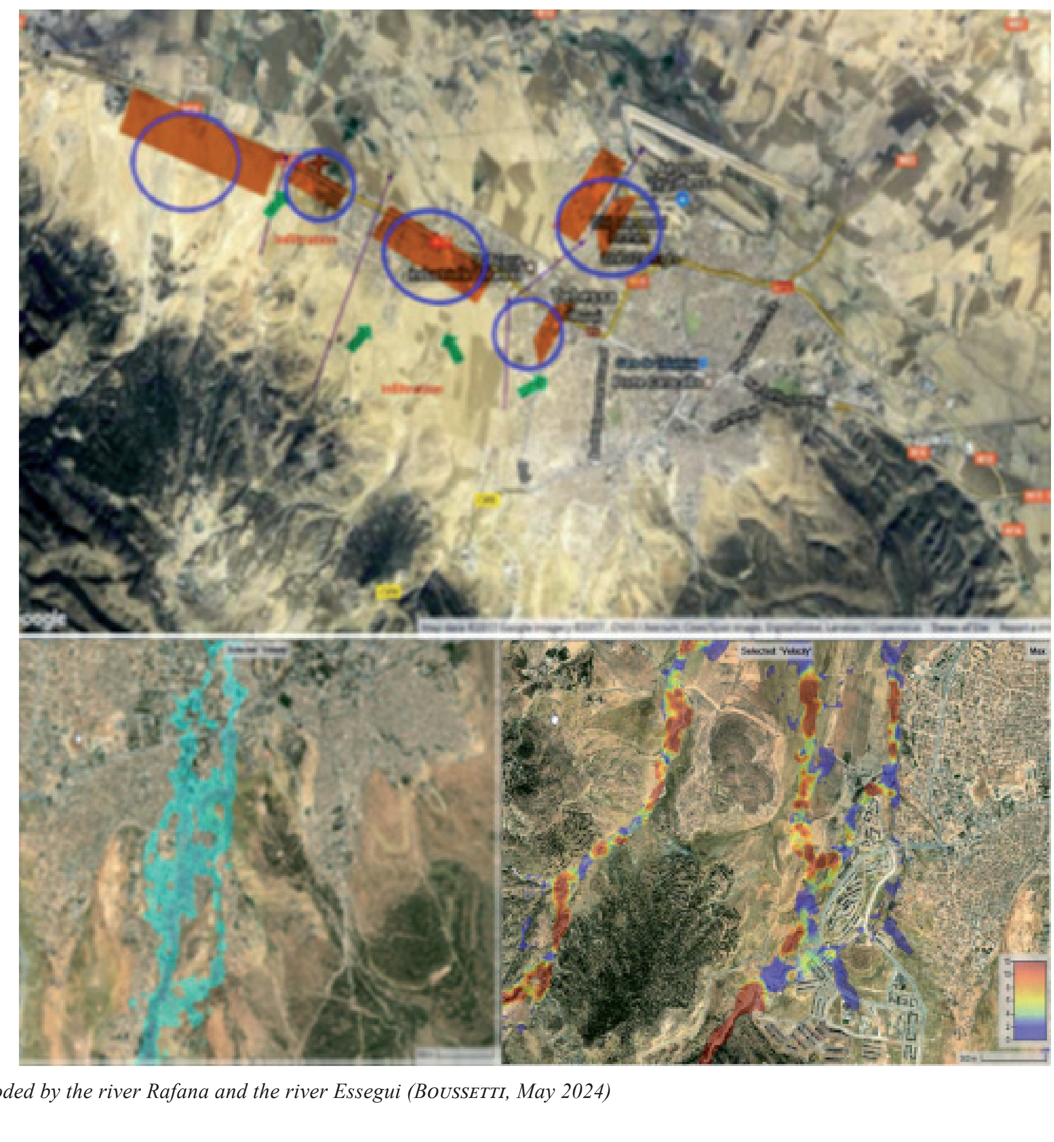

Fig. 9 - *Flooded by the river Rafana and the river Essegui (Boussetti, May 2024)*

Fig. 10 - Some Neighborhoods flooded by the river Essegui in the Municipality of Tebessa (Boussetti, May 2024)

significant threat to the city of Tébessa.

What exacerbates the risk of flooding in the city of Tébessa is the weakness of the external storm water drainage system due to solid waste, which impedes the flow of water in the river during floods. In addition, construction debris clogs the storm drains, preventing water from entering the drainage networks, leading to water stagnation (Fig. 10).

CONCLUSIONS

The objective of this study, in addition to identifying the most influential dimension of vulnerability in the occurrence of floods, was to determine the most vulnerable neighborhoods to flood risk in the city of Tebessa. Through the use of remote sensing and geographic information systems (GIS), it was possible to map the risk of flooding due to overflow in this semi-arid region. The application of the AHP statistical method allowed us to calculate the flood vulnerability index, taking into account five intrinsic factors related to the phenomenon of flooding in plains and valleys: slope, altitude, proximity to rivers and type of land use. High risk areas cover almost 32% of the study area, mainly in the urban neighborhoods of Tebessa, representing about 41% of these areas. These areas are generally high risk due to low slopes (< 12%), high drainage density, heavy rainfall, and significant socio-economic vulnerability.

We found that the river Nagues is the most vulnerable and is the first in terms of priority and vulnerability among the basins. It is necessary to take measures to reduce the impact of its floods on the urban environment of the city. The ZAAROUR River Basin comes next, with a similar level of risk, followed by the RAFANA River Basin, then the ESGUI River Basin, and finally the RAZALA River Basin. In fact, all of these basins pose a significant danger to the city of Tebessa, as confirmed by the floods of September 12, 2018, and those that occurred in 2020, 2021, 2022 and 2023.

In this context, flood hazard modeling of the watersheds is used to better estimate the return periods of historical floods, often indexed to centennial cycles. In our case, we consider Return Periods (Tr) of 50 and 100 years. The main result of this research is the development of a thematic map of regional water risk. This map could be used by local authorities in land use planning to minimize the risk of flooding in Tebessa.

A rational management of these floods is necessary and the risk map produced in this work is an important tool that can effectively contribute to decision making in the current context of climate change.

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