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Application of Two-Dimensional Hydraulic Modelling of Hydrological Risk Related to Urban Flood. A Case of the Taza City, Morocco

Hanae Bouiss[1*], Said Bengamra[1], Najat Amarjouf[2], Mostafa Oujidi[1], Iman Amar[1], Abdellatif Grari[1]

[1] Applied Geosciences Laboratory, Department of Geology, Faculty of Sciences, Mohammed First University, Oujda, Morocco

[2] Laboratory for Research and Development in Engineering Sciences "LRDSI", Department of Earth and Environmental Sciences, Faculty of Sciences and Techniques - Al Hoceima - Abdelmalek Essaadi University, Al Hoceima, Morocco

* Corresponding author's e-mail: bouiss.hanae@gmail.com

ABSTRACT

Flood Risk modelling and analysis have received plenty attention globally because of the growing rate of flood failures in maximum riverine regions. This work aims to map the flood hazard in an urban environment through two-dimensional (2D) modelling with the Iber software. The study area is the city of Taza, located between the Pre Rif and the Middle Atlas in the northeast of Morocco. The inputs to the 2D model are metrological, hydrological, topographical and geological data. The hazard map is developed using 2D hydraulic modelling. The results obtained show that the propagation of rainwater occurs rapidly due to the rugged terrain of the region studied and the impermeability of the soil.

Keywords: hazard, urban flooding, 2D hydraulic modelling, risk, Iber.

INTRODUCTION

Today, floods pose a real danger to property and people in most parts of the world. According to information from the International Disaster Database of the Center for Research on the Epidemiology of Disasters (CRED), floods have been the number one natural disaster in the world over the past two decades, accounting for 43% of disasters recorded globally. They cause more than 20,000 deaths per year and affect approximately 75 million people worldwide. As a result of global warming, Western Mediterranean countries are not immune to this natural phenomenon. Recent research shows the extent of flood damage in Spain, which is located in a western Mediterranean climate, for example (Díez-Herrero et al 2013; Hamitouche and Molina 2022; García-Feal et al 2018; Gil-Guirado et al 2022; Gonzalez-Cao et al 2022; Jiménez Barrado et al, 2019; Sánchez-García et al, 2019; Senent-Aparicio et al 2023). Morocco has not been spared either. It has experienced catastrophic floods that have caused significant human and economic damage in several regions of the country. Overall, 1,000 Moroccan sites at risk of flooding have recently been listed by the Water Research and Planning Department, including the Taza region, the area covered by this study.

Hydrological studies in Morocco are rare due to the insufficiency of meteorological data and the torrential behaviour of the watercourses, which are often ephemeral. The major periods of drought have led researchers to use theoretical calculations and hydrological modelling to qualify the flow rates of waterways and the extent of the flooding hazard (Amarjouf et al., 2011; Amarjouf et al., 2019; Amarjouf et al., 2021).

The city of Taza, located between the Middle Atlas and the Pre-Rif thrust sheets, in the northeast of Morocco, is threatened by flooding. The area has been strongly affected by floods that have caused maximum human and material damage. The most serious of these events have occurred in 1995, 2000, 2002, 2010, 2019 and 2022. In this study we will focus on that of 16 December 2022.

Indeed, the strong irregularity of the hydrological regimes in the urban centre of Taza, the nature of the often-impermeable soils, the disparity between a mountainous relief upstream and an alluvial plain downstream, and the area's rapid urbanisation reduce the infiltration of the soils and generate significant runoff. This causes torrential and violent floods. However, hydrological studies on the risks of flooding in the city of Taza are still rare. Here, we cite the work of Akdim et al (2010) and El-Hamdouny (2018).

This work aims to use 2D two-dimensional hydraulic modelling performed with the Iber software to map the risk of flooding in the city of Taza. Such modelling allows for visualisation of the hydrological behaviour of the torrential watercourses that cross the province of Taza, and especially that of the Larbaa River, the El Haddar Stream, the Dfali Stream and the Jouana Stream.

The Iber software is a two-dimensional numerical model that enables the simulation of water flows on a free surface. It is mainly based on the resolution of the Saint-Venant equations (Blade et al 2014; Gonzalez-Cao et al 2022). Many researchers have used this software as a hydraulic modelling tool (Amarjouf 2018; Grari et al 2020; Naiji et al 2019; Sañudo et al 2020).

The main objectives of this study are (1) the calculation of the peak flow for different return periods, (2) the simulation of the propagation of these flows in the sections studied and (3) the mapping of areas vulnerable to flood risk.

The validation of the results of this study is based on comparisons with the results of previous work and with the results of field surveys.

Study zone

The province of Taza is located in the north-eastern region of Morocco, in the southern Riffian part of the country. It is bounded to the north by the province of Al Hoceima at a distance of 140 km, to the west by the province of Fez at 120 km, to the east by the province of Guercif at 60 km and to the south by the Chains Mountains of the Middle Atlas. Morphologically, the Taza region is mostly located between two hydrological basins: the Moulouya basin to the east and the Sebou basin to the west (DPAT 2002) (Figure 1). The climate of the study area is subhumid. The average annual rainfall is around 580 mm.

Geologically, the study area is a transition zone between the middle Atlas causse and the southern Riffian furrow. At the level of the middle

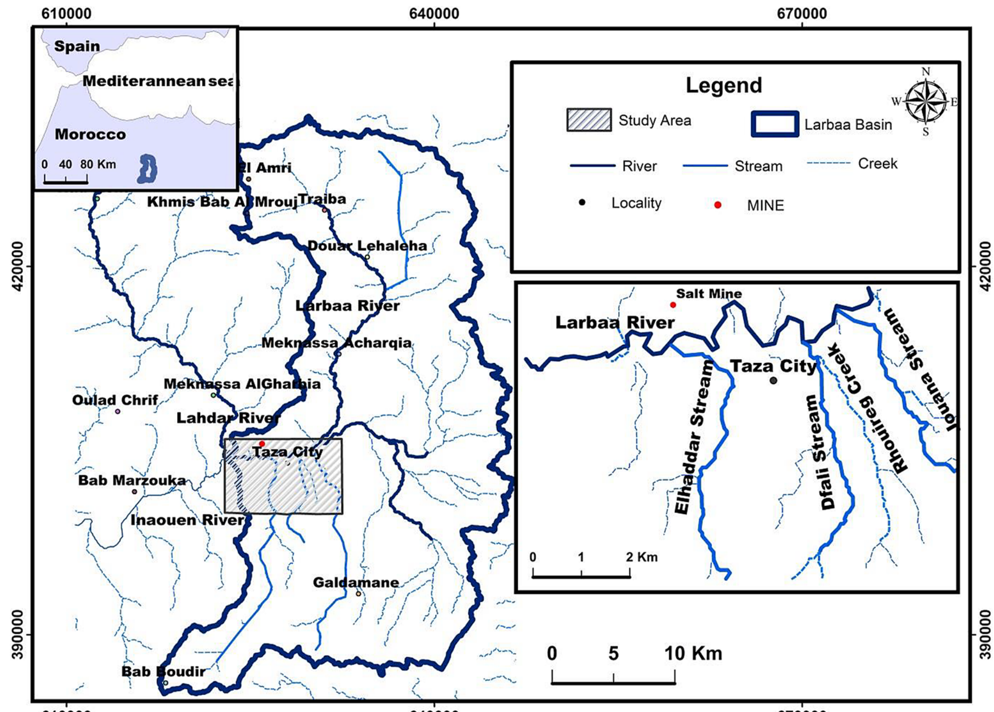

Figure 1. Geographical location of the study area

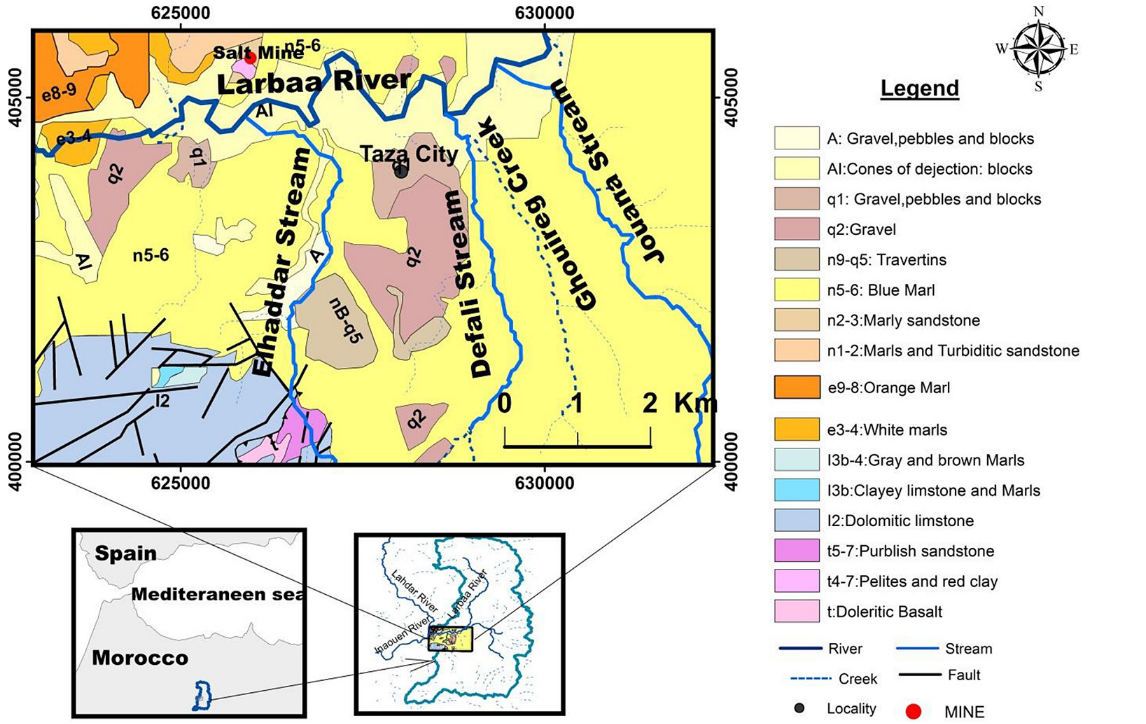

Figure 2. Geological map of the study area

causse, in the upstream part of the watersheds, the watercourses cross dolomitic terrains, limestone and the marl-limestone formations of the Lias (Vidal, 1971). Downstream, in the southern Riffian furrow, the watercourses intersect the Miocene marls (Cirac, 1985). The watercourse valleys are also sites of fluvial detrital sedimentation. There is a large dominance of marls, including the Upper Miocene (Tortonian) blue marls (LeBlanc, 1975). These formations are impermeable and very vulnerable to water erosion. In rainy periods, it promotes significant runoff, which generates faster and more violent floods. The impact of raindrops on soils and surface formation is strong. The first rains can easily cause the complete clogging of the soil void, reducing internal infiltration and causing runoff on the soil surface almost as soon as the rain begins to fall. As shown in Figure 2 the watercourses cross the formations of gravel, pebbles, blocs and marl.

Description of watercourses

The province of Taza is crisscrossed by a dense hydrographical network formed by a main watercourse named the Larbaa River and its tributaries: the El Haddar Stream, the Dfali Stream, the Ghouireg creek and the Jaouna Stream. These streams cause water overflows and road cuts, along with flooding of agricultural land located on their banks. Residents bordering rivers are still affected by floods, suffering from overflows on their homes during periods of flooding that disrupt their way of life. The damage resulting from floods is of great importance and requires rapid intervention and preventive measures to avoid.

Larbaa River

The Larbaa River watershed is located at the eastern end of the Inaouene watershed. It develops its watershed in the Eastern Pre-Rif over an area of approximately 281 km^2. Before joining the South Riffian corridor, it receives on its left bank two main tributaries: the Tarmast Stream in Ain Boukallal and the Boulajraf Stream, upstream of Taza. The Larbaa River crosses the town of Taza on its way to finally bring water to the main course of the Inaouen stream. The valley of the Inaouen Stream directs the geomorphological evolution of the region, functioning as the local base level because it centralises the hydrographic network (El Fellah, 1983).

El Haddar Stream

This stream is also called Taza Stream. It crosses the city of Taza between the Middle Atlas and the layers of the Pre-Rif, as well as National road N°6. It crosses a rocky landscape made up of limestone and dolomites (Zemzami, 2008).

Its point of confluence with the Larbaa River at the El Melha district level causes catastrophic flooding.

Dfali Stream

The Dfali Stream, which is 15 km long, originates in the Middle Atlas. Its watershed covers an area of 28 km². It is a tributary of the Larbaa River at the level of the city of Taza.

Jouana Stream

This stream, which is about 18 km long, is the only southern tributary of the Larbaa River. It rises southeast of the town of Taza. Its northern section crosses an urban area.

Ghouireg creek

The Ghouireg creek has its source in the north of the Middle Atlas, delimited to the east by the Jaouna watershed and to the west by the Dfali watershed; it descends in its direction as far as the urban area of Taza at the meeting point with the national road N° 6, its watershed area covers an area of about 8 Km².

Figure 3 illustrates that the slopes of watercourses studied vary between 0 % and 4%. Table 1 below summarises the characteristics of the watercourses studied in function of lengths of watercourses, slope and flow type. The most important Watershed area is that of Larbaa River, whose area is 281 Km². Its flow is permanent, throughout the year. It is drained by the following streams: Jaouna Stream, Dfali Stream, El Haddar Stream and Ghouireg creek.

MATERIALS AND METHODS

To model the flow and propagation of water during floods using two-dimensional modelling software, the following steps must be followed: Data collection, hydrological study and flood, hydraulic modelling with Iber 2D and drawing the flood vulnerability map.

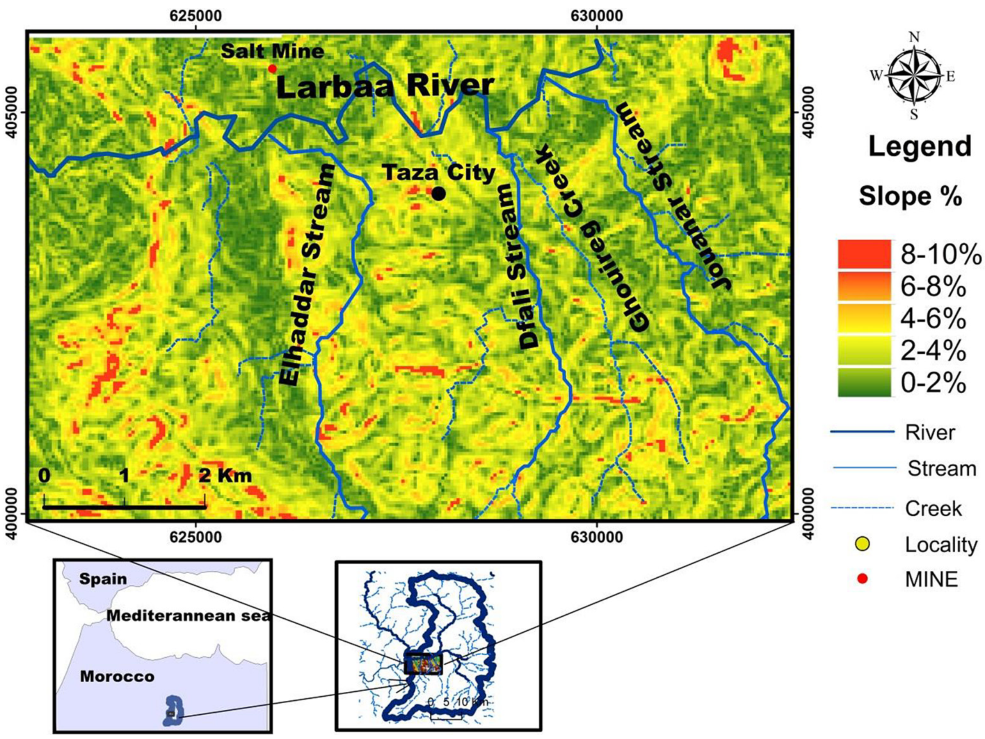

Figure 3. Slope map of study area

Table 1. Characteristics of the watercourses studied

Watershed	Area (km²)	Lengths of watercourses (km)	Slope in %	Flow type
Larbaa River	281	43	2.14	Permanent
Jaouna Stream	48	18	4.95	Permanent
Dfali Stream	28	15	8.04	Permanent
El Haddar Stream	43	15	8.99	Permanent
Ghouireg creek	8	7.5	5.10	Non permanent

Data used

The digital terrain model was downloaded from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) sensor with a resolution of 30 metres. Precipitation data was collected from the Taza Water and Forests Agency in Excel file format. The satellite image was downloaded from the Global Mapper. River flows were calculated by mathematical formulas, and flood hydrograms were developed with the Soil Conservation Service (SCS) method in order to calculate the peak flow of micro-watersheds.

Hydrological study

To delineate the watersheds of the rivers crossing the study site, and determine their physical characteristics, we processed the digital terrain model (DTM) using Arc-GIS software.

In order to determine the rains of different frequencies used in the flow calculation formulas, we carried out a statistical processing of the rainfall data recorded at the Taza station (the nearest station). We made an adjustment to the maximum daily rainfall of a 30-year series (1986-2016) according to Gumbel's law.

We used the Soil Conservation Service (SCS) method to calculate discharges. This method is based on the calculation of peak flow versus peak volume, versus river basin factors, and versus precipitation frequency (Bales and Betson, 1982; Chen, 1982; Garen and Moore, 2005).

The point flow is estimated with the following formula:

$$q = \frac{0.00208\, AQ}{\frac{D}{2} + 0.6T_c} \tag{1}$$

where: q – peak runoff rate (in m^3/s);
A – area of watershed (ha);
Q – runoff volume (in mm relative to watershed);
D – storm duration (h);
T_c – concentration time (h).

Hydraulic modelling with Iber 2D software

The Iber software is a 2D mathematical model to simulate river flow. It solves 2D depth-averaged shallow water equations using the finite volume method, which is widely used in computational fluid dynamics (Bladé et al. 2014; Fonseca and Santos, 2018; Gil-Guirado et al. 2022; Gonzalez-Cao et al. 2018; Gonzalez-Cao et al. 2022; Versteeg and Malalasekera, 2007). Iber software is specifically designed to meet the technical needs of hydrographical confederations in the application of water directives and sectorial legislation. Some of its areas of application are the simulation of flow in natural channels, the assessment of flood zones, the calculation of preferential flow zones, the hydraulic calculation of pipelines, the hydraulic calculation of canal networks, the estimation of tidal currents in estuaries, bed sediment stability analysis, and studies on erosion and sedimentation processes by transport of granular material (Bladé et al,. 2014). As noted above, this software is based on the resolution of the Saint-Venant equation (Garrote et al., 2016).

$$\frac{\partial H}{\partial t} + \nabla(HV) = q \tag{2}$$

$$\frac{\partial V}{\partial t} + V(\nabla V) + g\left|\nabla Z + \frac{V\|V\|}{K^{2}_{5}\; H^{4}_{3}}\right| = 0 \tag{3}$$

where: H – water height (m);
V – water velocity vector (m/s);
q – amount of input (m^3/s);
z – elevation of the free surface.

The process steps to obtain a simulation with the Iber software are (1) definition of the geometry of the stream, (2) designation of initial and boundary conditions, (3) creation of the model mesh for mathematical calculations, (4) definition of channel roughness, and (5) calculation and extraction of results in the form of geographical maps.

Flood vulnerability map

The flood vulnerability map was produced by studying the land use which presents direct and indirect economic damage. We took the following steps to produce the flood vulnerability map: (1) a 'static and dynamic' diagnosis of the components of the territory and (2) the use of GIS 'Geographic Information System' for the processing and spatialisation of data collected in the field (D'Ercole, 1994; D'Ercole and Metzger, 2009; Ducher and Rode, 2009).

Table 2 illustrates the indices used in this work for flood vulnerability maps. Unpopulated areas with high soil permeability are qualified as areas of low vulnerability to flooding. While urbanized areas whose soils are impervious and favour runoff are qualified as areas of high flood vulnerability. Finally, area with urban vegetation is qualified as medium flood vulnerability.

Table 2. Flood vulnerability index

Land use	Flood vulnerability indicator	
	Numeric value	Gravity
Bare ground Sparse vegetation Forests Unclassified area Dense vegetation	0	Low
Urban vegetation	0.5	Medium
Industrial zone Infrastructure Residential area River	1	High

Figure 4 summarizes the methodological framework and data collected used to obtain the results of this study.

RESULTS AND DISCUSSION

The main results for the land use map of study area, flood vulnerability map, flood depth map, flood velocity map, flood hazard map, flood risk map and validation of the results obtained are detailed below.

The land use map of the study area showed seven classes. The table below defines the classes according to their areas: dense vegetation, cereal crop, residential area, forests, rivers, unclassified area and olive growing. The most important land use is residential area it covers an area of 22 Km².

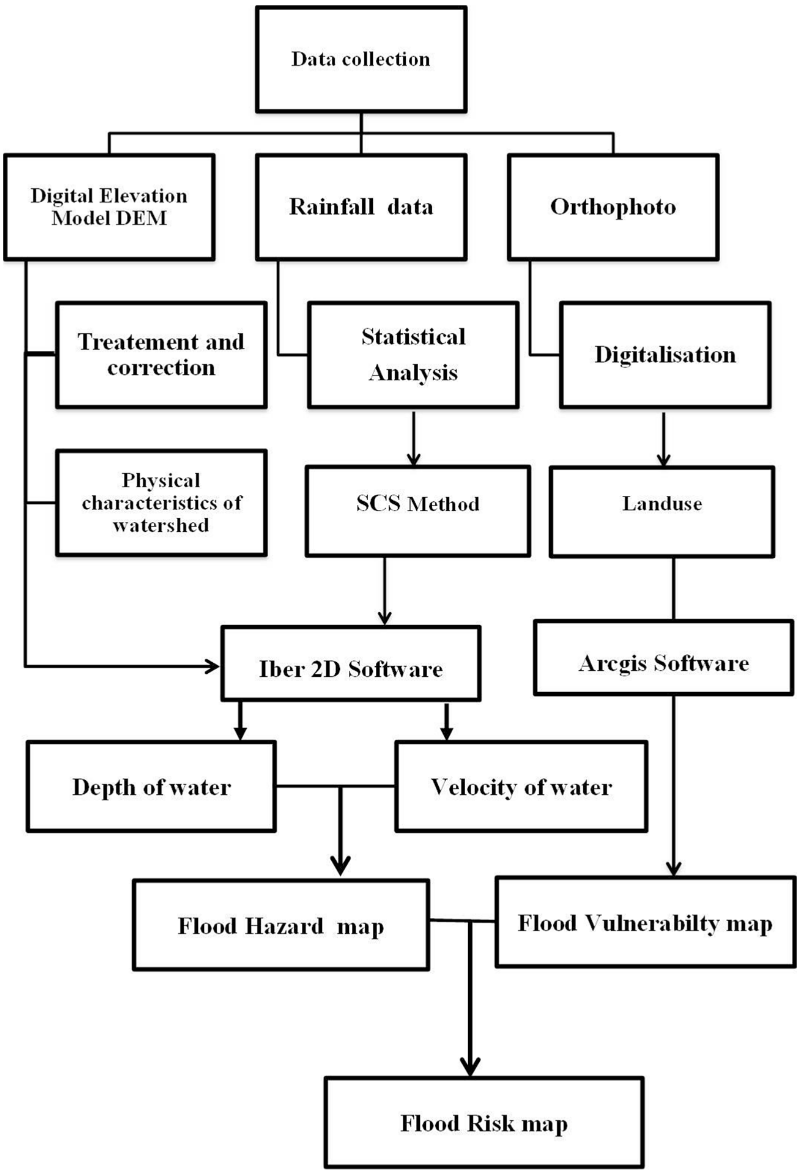

Figure 4. Methodological framework

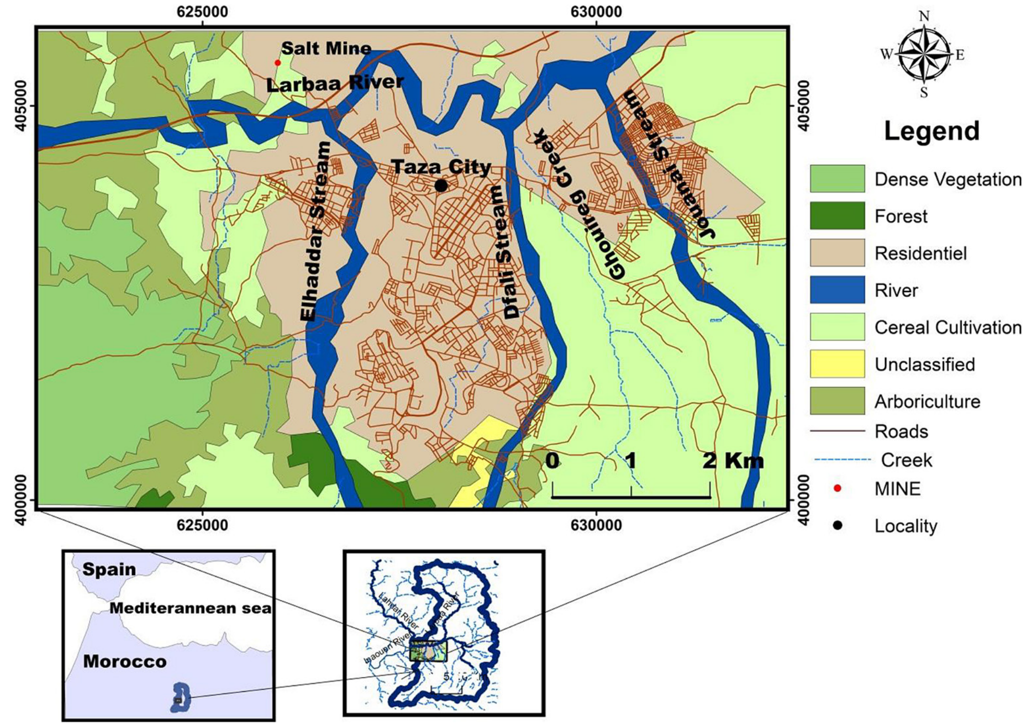

Figure 5. Land use map of study area

Table 3. Landuse classes

Land use classes	Area in km²
Dense vegetation	6 km²
Cereal crop	21 km²
Residential area	22 km²
Forests	1,5 km²
Rivers	3,5 km²
Unclassified area	2 km²
Olive growing	9 km²

Table 3 summarizes the land use classes according to their area.

Flood vulnerability map

This map was produced following a field investigation and according to the declaration of the disasters of the old floods as well as the flood of 16 December 2022 that affected study area. As shown in Figure 6, the most vulnerable area is the area between the two watercourses: the El Haddar Stream and the Dfali Stream, as well as the banks of the Larbaa River.

Vulnerability to flooding is closely related to the growth of urbanisation, especially at the level of the districts bordering the banks of the watercourses. It is important to point out that the zones of high vulnerability which are between Elhaddar stream and Dfali stream are not flooded directly by the waters coming from these two watercourses. This zone submerged due to the impremeablity of the soil - due to the strong urban - that generate significant runoff: This is the case of Taza city. The same thing for the neighbourhoods which are close to the point of confluence of the Ghouireg

Table 4. Flood vulnerability classes

Flood vulnerability range	Land use	Area in km²	% of the total area
Low vulnerability	Bare ground Sparse vegetation Forests Unclassified area Dense vegetation	32 km²	49.23 %
Medium vulnerability	Urban vegetation	6 km²	9.23%
High vulnerability	Industrial area Infrastructure Residential area River	27 km²	41.54%

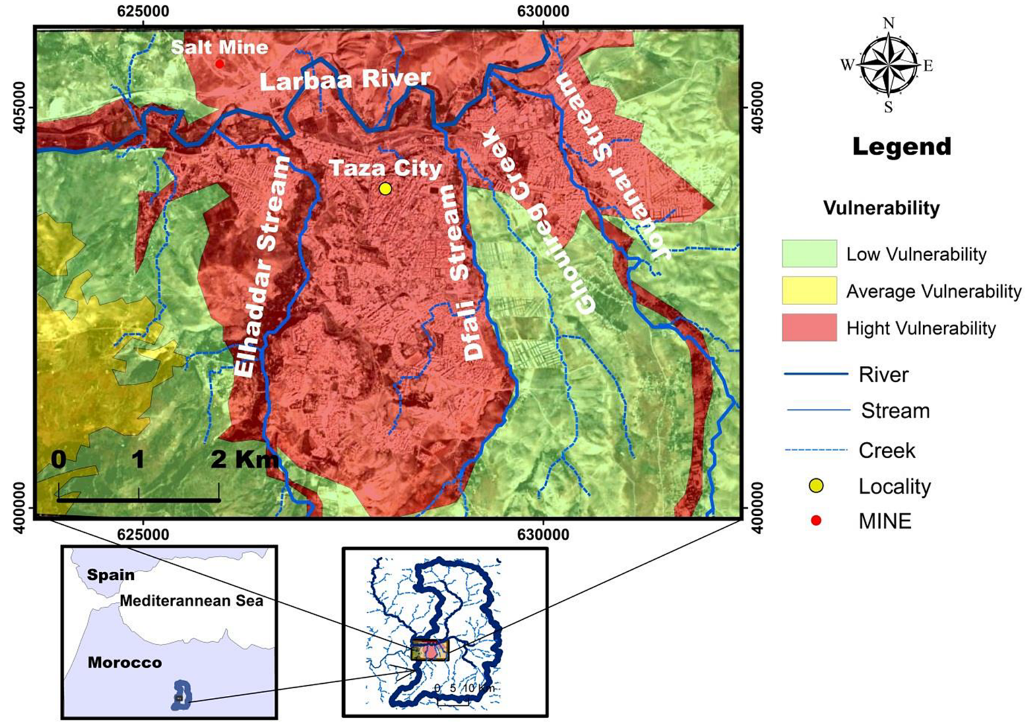

Figure 6. Vulnerability map of study area

creek and Jouana streams, as well as the urbanized areas on the banks of the Larbaa River.

Table 4 presents the vulnerability classes in study area. The zone of low flood vulnerability ranges presented by high soil permeability: Bare ground, sparse vegetation, forests, unclassified area and dense vegetation presents 32 Km^2 represents almost 50% of the studied zone. The medium flood vulnerability range is represented by urban vegetation and constitutes 9.23% of the total area. Finally, the high flood vulnerability range represented by area with low and zero permeability soils: presents 41.54% of the total area.

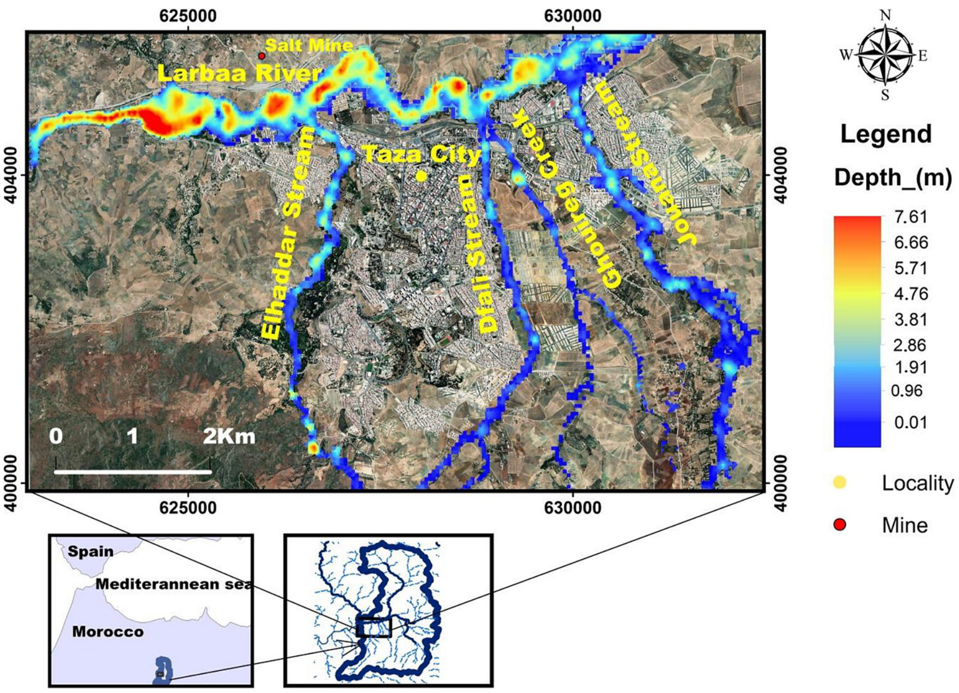

Figure 7. Flood depth map of study area

Flood depth map

According to Figure 7, we note that the height of waters which are between 4.76 m and 7.61 m are situated at the level of the bed of the Larbaa River. The water heights between 1 m and 3.81 m are found near the areas of the studied watercourses and the point of their confluence with Larbaa River.

Table 5 shows that the areas where the heights of the flood waters are between zero and four meters represent 69.25% of the flooded areas, therefore, it constitutes 12.76 % of the study area. The areas submerged by water whose heights are between two and four meters represent 21.66% of the flooded area, then it present only 4% of the study area. While the areas submerged by water heights between four and six meters do not exceed 5.58 % of the flooded area.

Flood velocity map

Figure 8 shows that the flood velocities are between 1.63 m/s and 3.20 m/s. This is explained by the slope of the watercourses which is between 2% and 4%. For the Ghouireg creek the flood velocity is too low between 0 m/s and 0.46 m/s because of its low slope.

From Table 6, we notice that the areas with flood water propagation speeds are between 0 m/s and 1 m/s constitute 69.25% of the flooded area.

Table 5. Flood depth ranges

Depth of water	Area (km²)	% of flooded area	% study area
0–2 m	8.31	69.25 %	12.76 %
2–4 m	2.60	21.66 %	4 %
4–6 m	0.67	5.58 %	1.03 %
> 6 m	0.51	4.25 %	0.78 %

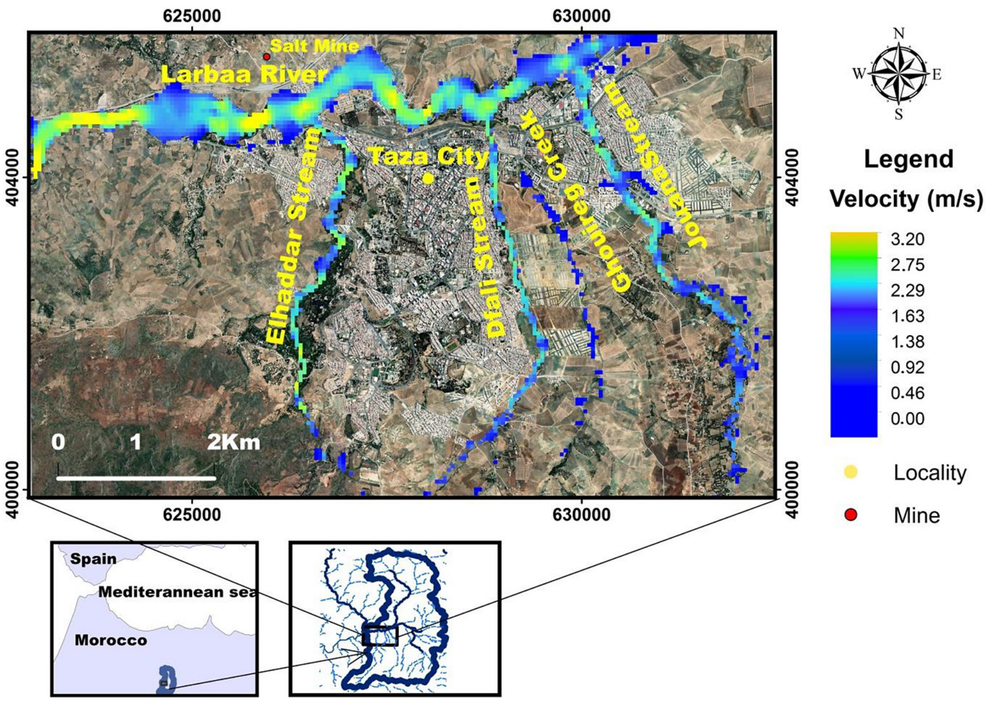

Figure 8. Flood velocity map of study area

Table 6. Flood velocity ranges

Velocity of water (m/s)	Area (km²)	% of flooded area	% study area
0–1	8.31	69.25%	12.78 %
1–2	3.52	29.33%	5.41%
> 2	0.16	1.33%	0.24%

Whereas the zone with a speed between 1m/s and 2 m/s represents 29.33% of the flooded area. Also, the land with water velocity exceeds two meters represents only 1.33% of the flooded area, which is 0.24% of study area.

Flood hazard map

The flood hazard map obtained directly by two-dimensional modelling using the Iber 2D software shows that the high hazard zone is limited to the bank of the Larbaa River. The area qualified as average hazard is that of the confluence of the watercourse Elhaddar stream, Dlali stream, Ghouireg creek and Jouana stream with Larbaa River, as shown in the Figure 9.

As shown in Table 7, the area of high flood hazard range represents 59.75% of the flooded area, therefore 11% of the study area. The high hazard range focuses mainly on the major beds and floodplains of the Larbaa River. At the level of the major beds of the Larbaa River, the land has a slight slope between 0 and 2% favouring runoff and stagnation of water. Moreover, the lithology of the soils, which are essentially made up of dejection cones, favours the stagnation of water during rainfall.

Flood Risk map

The flood risk map shows three areas with risk levels ranging from low to high.

The analysis of the flood risk map obtained reveals the existence of several points threatened by the overflow of water from the sections studied:
- the overflow of the Jouana Stream threatens the urban construction in the Al Qods III district. The floodwater affects the edges of the Al Qods mosque as well as commercial spaces. The water depth reaches 3 m at the level of the course channel of water and 2 m at the level of the banks.
- the overflow of the Dfali Stream affects the district of Bayt Ghoulam to a depth of 2.27 m.
- the overflow of the Elhaddar Stream at the confluence between it and the Larbaa River leads to the submersion of agricultural land used to grow olive trees to depths that can reach 3m.
- upstream of the Larbaa River, northeast of the city of Taza, the overflow threatens the new

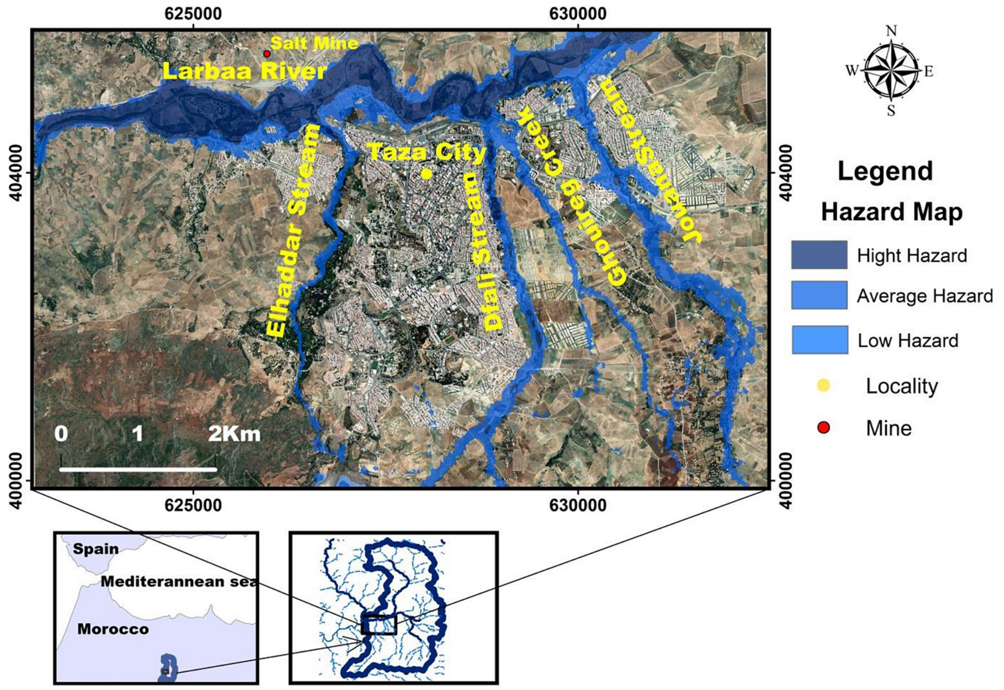

Figure 9. Flood hazard map of study area

Table 7. Flood hazard ranges

Flood hazard	Area (km²)	% of flooded area	% Study area
Low	0.92	7.66%	1.41%
Medium	3.67	30.58 %	5.64%

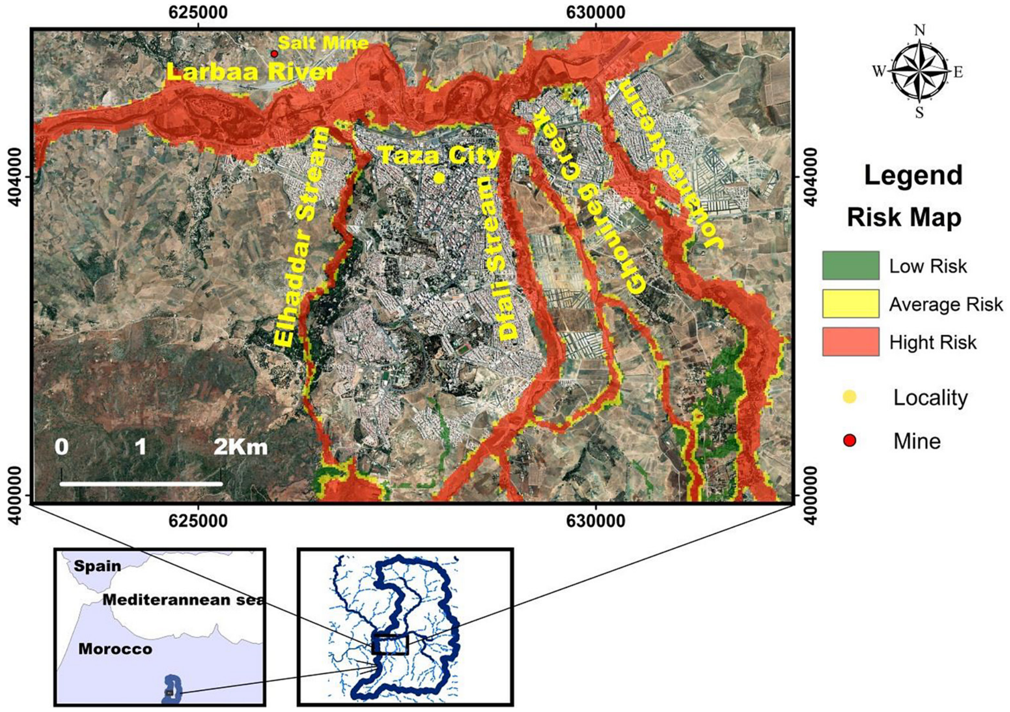

Figure 10. Flood risk map of study area

commercial space Souk Latnin, which could be flooded with up to 4 m of water.

- along the Larbaa River, the depth at bed level reaches 5.5 m, and the watercourse overflows, threatening the Asdour N1 and N2 districts.
- even further downstream from the Larbaa River, the depth of the water is around 6.62 m, threatening the El Melha district, the El Melha School and the old ammunition depot.

Finally, the risk of flooding is very important at the level of the banks of the Larbaa River and the major beds of Jouana stream, also, at the point of confluence between the three watercourses: Dfali stream, Ghouireg creek and Larbaa River, where the commercial constructions and the residential districts are concentrated.

The Table 8 shows the flood risk damage with area of each range and percentage of flood area and study area. The high flood risk damage range covers an area of 9.77 km^2 which means 81.42% of flood area and 16.81% of the study area. This is the consequence of the strong urbanism on the major beds of the rivers studied.

Validation of results

The results obtained via the hydraulic simulation of floods are quite convincing. Indeed, the comparison of the modelled results with the data collected directly on the ground shows the same extension of the zones vulnerable to flooding. For example, by comparing the results of hydraulic simulations of the Larbaa River with the traces of the recent floods on 16 December 2022, we can see that the margin of error between the two results is limited to a few metres.

In comparing our results with those obtained in the work of Gonzalez-Cao (2023) in Badajoz in Spain, we notice a similarity, especially at the level of the propagation of floods on impermeable soils. The height of the waters does not exceed 12 m.

The Table 9 shows a comparison between the water heights calculated by the Iber software and that observed in the field during the flood on 16 December 2022. Generally the difference between the heights of water observed at the time of floods and those calculated theoretically does not exceed 60 cm.

Table 8. Flood Risk damage

Flood risk	Area (km²)	% of flooded area	% study area
Low	0.83	6.92 %	1.42 %
Medium	1.40	11.66 %	2.42 %
High	9.77	81.42 %	16.81 %

Table 9. Water height

Watercourses	Max height calculated by Iber 2 D	Max actual observed height	Difference between the two values
Larbaa River	7.61 m	8.2 m	-0.59 m
Elhaddar Stream	3.78 m	4.6 m	-0.82 m
Dfali Stream	2.27 m	2 m	0.27 m
Jouana Stream	2.8 m	2 m	0.8 m
Ghouireg Creek	1.90 m	1.0 m	0.9 m

CONCLUSION

The results obtained allowed for the evaluation of the vulnerability of the study area to flooding and the precise identification of agglomerations, equipment and infrastructures likely to be affected by flooding. These areas largely correspond to the dwellings and cultivated land located in the area downstream of the city of Taza (El Quds district, Souk Latnin, El Melha district, Asdour N°1 district, the ammunition depot, etc.).

Impermeable soils and accelerated and uncontrolled urbanisation at the level of the beds of the rivers explain the generation of torrential and violent floods, which have heavy consequences, both human and material.

The use of the Iber 2D software allowed us to deduce the energy of the propagation of the floods at the level of Taza city, and enabled us to visualise the extent of the waters that often flood the region. The validation of our results with the floods on 16 December 2022 confirms the quality of our results.

The results of this work constitute a tool for orientation, decision-making assistance and support for local and territorial communities involved in various development projects in Taza city.

Acknowledgments

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