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ORIGINAL PAPER

Flood risk mapping using multi-criteria analysis (MCA) through AHP method case of El-Ham wadi watershed of Hodna basin (Algeria)

Nour El Houda Belazreg[1] · **Mahmoud Hasbaia**[1] · **Zekai Şen**[2] · **Ahmed Ferhati**[1]

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Abstract

Following the rapid increase in flood events in recent years, flood risk assessment and mitigation have become a necessity. The purpose of this study is to develop updated and accurate flood risk and hazard maps in the El-Ham watershed within the large Hodna basin (Algeria). In order to achieve this objective and to select weights of contributing criteria to flood risk, geographical information system and multi-criteria analysis along with the application of analytical hierarchy process technique have been used. Factors considered to be the cause of flooding are slope, annual maximum daily precipitation, drainage density, elevation, land use/cover and soil type. In addition to the hazard, population density has been also used to determine the risk of flooding in El-Ham watershed. The percentages of weights obtained for each parameter are 39% for slope, 25% for drainage density, 18% for rainfall, 9% for elevation, 6% for land use/cover and 3% for soil type. For validation of these weights, a consistency ratio is then calculated. Main outcomes present a high flood potential, especially in the North-Eastern, North-Western and Central part of the study area. However, this high potential decreases further when one goes toward the South. This research suggests that the chosen criteria are sufficient to obtain a reliable and simplified flood risk map. Any additional parameters would add more details to the risk map using hydraulic and/or hydrological models to generate flood hazard maps such as RRI and HEC-RAS models.

Keywords Flood risk · Mapping · Multi-criteria · GIS · AHP · El-Ham wadi

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1 Introduction

Floods are the main natural disaster risk in the world in terms of human and economic losses. Likewise, they can cause serious damages to the environment. Globally, almost one billion people live in floodplains. With the increase in anthropogenic activities and urbanization, floods have become more harmful, especially in areas that are at risk of flooding.

Recent events in 2021 indicate that flood and flash flood events affect many countries and societies. Scientists state that natural disasters such as droughts and floods are becoming more frequent and severe due to climate change. Intensive rainfalls triggered severe flooding and landslides in Turkey, Iran, Oman, Saudi Arabia, Japan, China, Germany, Belgium and France (WMO 2021). In Africa, numerous flooding events are also recorded in 2021, following heavy rains in Niger, Cameroon, Sudan, Ethiopia, Chad and Ghana (the period from 26 July to 14 August). In Algeria from the same year, severe flooding of Oued Meknassa, Boussaada, Laghouat, Chelef, Batna and Médéa caused dozens of deaths and thousands of injuries.

Proper flood risk assessment is an essential component of flood mitigation, especially in urban areas. It considers the consequences of floods on population, economy and environment. Flood risk estimation can be generated by three main methods: analysis of flood frequency, analysis of storm progression, and flood hazard maps (Rincón et al. 2018). Flood risk assessment is a combination of hazard and multiple vulnerability dimensions.

Much research has been done in the field of flood hazard and risk assessment and increasing damage severity. They provide valuable information that complements flood analysis and quantification. Integrating multi-criteria analysis (MCA) approaches with GIS and analyzing flood-prone areas and conduct risk analysis to assess effective causal factors have been widely used. MCA is a decision-making tool developed for solving complex multi-criteria problems involving qualitative and/or quantitative aspects of the problem (Mendoza et al. 1999). It mainly focuses on flood risk mitigation assessment rather than flood risk mapping (Sharma et al. 2017).

Numerous factors causing flooding can be used to derive flood risk maps, namely monthly and annual rainfall, main drainage channel slope, drainage density, topographical factors, flood frequency, land use/cover, elevation, soil type, flood depth, flood duration, flood velocity, economic and social vulnerability (Yalcin et al. 2004; Raaijimaket et al. 2008; Deng et al. 2010; Scheuer et al. 2011; Abdalla 2012; Musungu et al. 2012; Sharma et al. 2012; Elsheikh et al. 2015; Rincón et al. 2018; Mokadem et al. 2018; Saidi et al. 2019; Ogato et al. 2020) through analytical hierarchy process (AHP) method. Some studies were applied flood modeling approaches to demonstrate the feasibility of flood modeling in data-scarce environments and limited resources, others have generated flood hazard and risk maps for different scenarios, each with different criteria taking into account the floodplain, the distance to the streams, the height above the nearest drainage, the number of flow curves, the total precipitation and the effective precipitation maps.

The main objective of the current study is application of MCA concept, GIS and AHP weighting methods for the El-Ham wadi sub-basin flood hazard and risk map generations in the Hodna large basin in Central Algeria. This objective is achieved by preparation of flooding causative factors maps such as slopes, elevation, drainage density, rainfall, population density, soil type and land use/cover parameters.

2 Study area

The Hodna basin is a plain surrounded by mountains and characterized by a 26,000 km^2 landlocked bowl (Hasbaia et al. 2012; Hasbaia and Adoui 2015). It is located between latitudes 36°10′ in the North and 34°29′ in the South and longitudes 3°02′ West and 6°11′ East (Zeroual et al. 2021; Belazreg et al. 2022; Ferhati et al. 2023). Precisely, it is situated in the center of Algeria where the lowest and middle parts consist of a salty lake called Chott-El-Hodna. This lake is covered only by water in winter, dry and covered with salt crust in summer.

In the present study, the El-Ham sub-basin, which is one of the eight sub-basins in the large Hodna basin (Belazreg et al. 2021), is chosen. The El-Ham watershed is located in the north-western part of Hodna basin, with maximal and minimal altitudes equal to 1799 m and 432 m, respectively (see Fig. 1).

3 Methodology and materials

The data considered in this study are digital elevation model (DEM) of Hodna basin, 53 years (1966–2019) of annual maximum daily precipitation (AMDP) data for the study area from the National Hydraulic Resources Agency (ANRH), Algeria population density (2008 census) and global land cover/use.

Integration of remote sensing data with GIS and AHP is very effective tool for flood vulnerability data generation (Elsheikh et al. 2015; Rimba et al. 2017). The criteria used in this study are chosen because of their relevance and importance in the study area, such as precipitation, slope, drainage density, elevation, soil type and land cover/use (Fig. 2).

Ranking and rating methodologies have been used (Sharma et al. 2017; Hu et al. 2017; Mokadem et al. 2018; Saidi et al. 2019; Ogato et al. 2020). Ranking is assigned to each decision item that reflects the degree of importance it influences the decision; while ranking is somewhat similar to rating but numerical scores are assigned to indicate the level of importance it has.

3.1 Analytical hierarchy process (AHP) methodology and weighting procedures

The AHP method is developed by Saaty (1980) to develop multi-criteria decision (MCD) problems, which takes pairwise comparisons as input and produces relative weights for each criterion as output on a scale of 1 to 9 (Saaty 1977; Malczewski 1996; Yalçın et al. 2004; Rincon et al. 2018). The parameters need to be weighted to determine the degree of impact of each on the flood risk in the study area (Gosh and Kar 2018; Saidi et al. 2019). The most important criterion has more weight in the overall evaluation (Yalçın et al. 2004; Dall'Osso et al. 2006).

To calculate these weights, the main steps are as follows (Yeganeh et al. 2014; Elsheikh et al. 2015; Rimba et al. 2017; Ogato et al. 2020):

- Establishment of the pairwise comparison matrix which depends on intensity importance values ranged between 1 and 9 of Saaty scale (1980). Five criteria have been selected, namely rainfall distribution, slope, drainage density, runoff coefficient

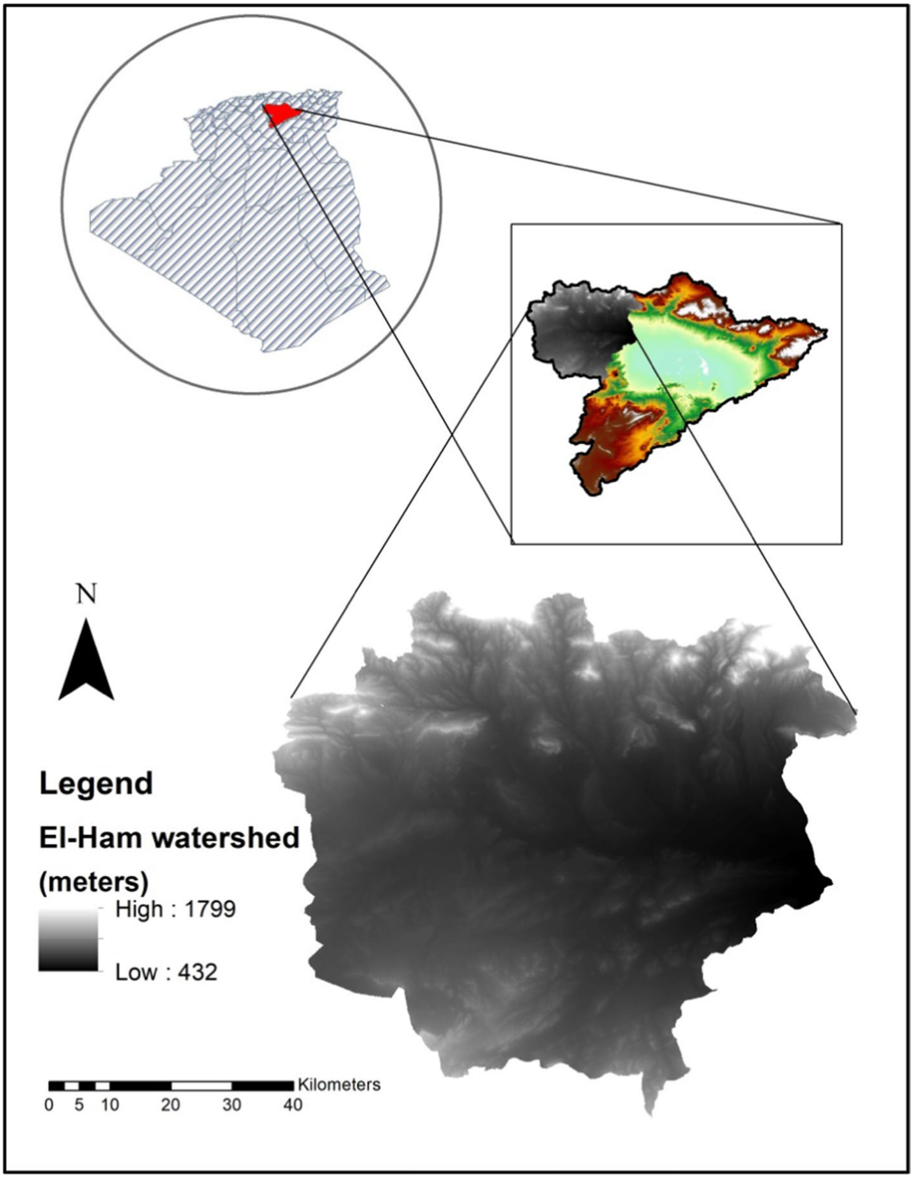

Fig. 1 Geographical location of El-Ham watershed in the Hodna basin (Algeria)

and soil type. Other values of the matrix are the inverse of each of the importance values;

- The next step consists of a linear normalization of the matrix. Each of the previous values of the pairwise matrix is divided by the total sum of each criterion in order to retrieve the normalized values;
- Each row is then averaged to obtain the final weights (Eq. 1);

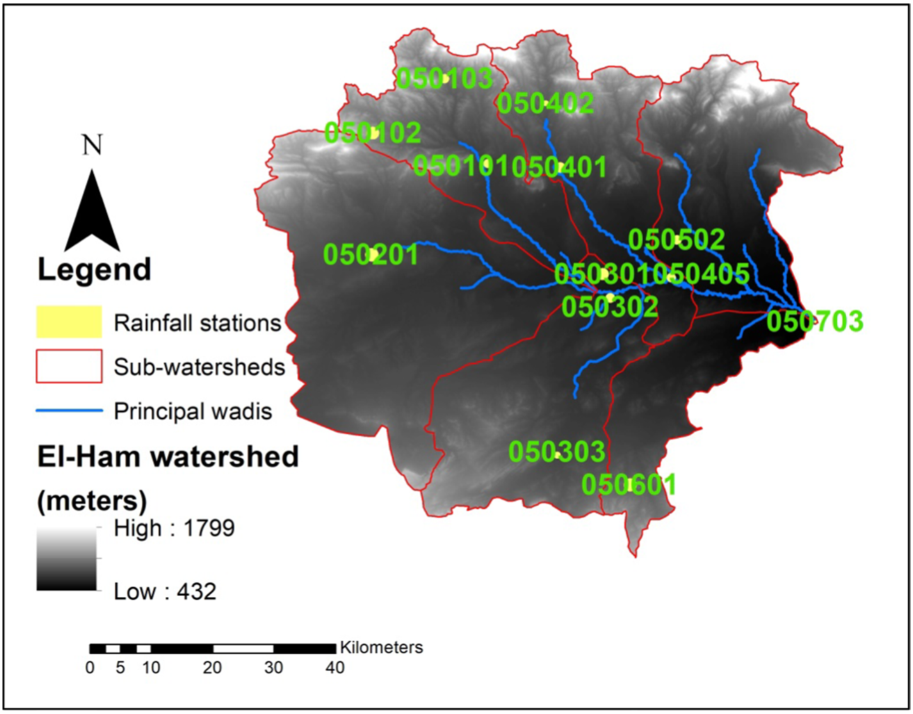

Fig. 2 Location of the gauging stations in El-Ham wadi watershed

$$\text{Weight (criterion)} = \frac{\text{Weighted sum vector}}{n} \tag{1}$$

- To confirm the level of consistency of the obtained results, calculation of the consistency index (CI) and the consistency ratio (CR) is then calculated. CI and CR should be less than 10%;
- CI is calculated by Eq. 2. Three parameters are necessary to calculate in order to obtain the consistency index, which are the weighted sum vector, the consistency vector and the Lambda. The first one is calculated by do the sum of normalized matrix values for each row. The second one is the ratio between the weighted sum vector and the weights. Finally, Lambda is the average of the consistency vector;
- The final calculation is the consistency ratio (CR) which is the ratio between the consistency index and random index (RI). RI values are retrieved from Table 1 (Saaty 1980) following the size of the matrix (Yeganeh et al. 2014; Sharma et al. 2017; Saidi et al. 2019). See Eq. 3.

Table 1 Random Index (RI) values for the consistency ratio (CR) calculation (Saaty 1980) (Where N: Number of criteria or number of parameters compared)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57

$$\mathrm{CI} = \frac{\lambda - n}{n - 1} \tag{2}$$

where CI is the consistency index, λ is the average of the consistency vector, and n is the size of the matrix.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3}$$

3.2 Flood hazard mapping

Hazard refers to the possible future occurrence of natural or man-made physical events that may have adverse effects on sensitive and exposed elements (UNDHA 1992). For index selection and extraction, hazard factors included in this study are elevation (E), drainage density (DD), slope(S), rainfall (R), land use/cover (LULC) and soil type (ST). These hazard factors are selected through literature review and expert views.

Final hazard map and all other contributing factors to flood hazard are reclassified into five (5) classes from the very low to the very high susceptibility of flooding. This classification uses Natural Breaks technique. Equation (4) presents the flood hazard index for different criteria multiplied by its calculated weight using AHP technique.

$$\mathrm{FHI} = (S * W1) + (DD * W2) + (R * W3) + (E * W4) + (\mathrm{LULC} * W5) + (\mathrm{ST} * W6) \tag{4}$$

where FHI is flood hazard index, S is slope, DD is drainage density, R is rainfall, E is elevation, LULC is land use/cover, ST is soil type, and finally, $W1$, $W2$, $W3$, $W4$, $W5$ and $W6$ are the appropriate weight parameters.

Main steps and different tools in ArcGIS used to generate the previous mentioned maps in order to obtain the hazard map are given in details in the flowchart presented in Fig. 3.

- Elevation (E)

Elevation data were extracted from the digital elevation model (DEM) with a spatial resolution of 30 m. The DEM data were retrieved from the Shuttle Radar Topography Mission (SRTM) (Hu et al. 2017). Final map is then reclassified into 5.

- Drainage density (DD)

Drainage density is a fundamental concept in hydrology as it is the ratio of total drainage lengths per catchment area. Permeability is controlled by the wearability of surface materials, vegetation, slope and duration. It is an inverse function of infiltration (Abdalla 2012; Mokadem et al. 2018; Ogato et al. 2020).

The extraction process of river network density is obtained using several tools such as *fill*, *flow direction*, *flow accumulation*, *raster calculator* and also the *kernel density* tools. This classification is generated using the Natural Breaks (Jenks) classification where high classification means high possibility of flooding, where low suggests low probability of flooding.

- Slope (S)

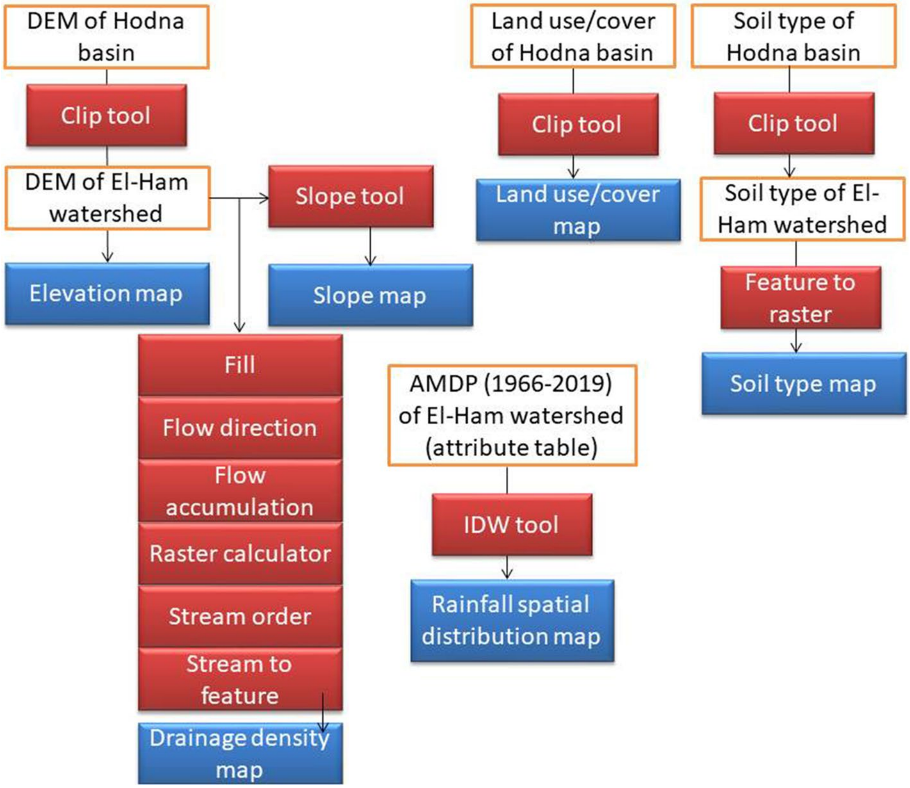

Fig. 3 Procedures for generation of the hazard map using ArcGIS software

The movement of precipitation depends on the drainage basin slope, which is an important factor in determining the speed of the discharge. Low slope values increase the risk of water accumulation on flat surfaces (Ogato et al. 2020) in contrary to high slope which decrease the risk of water accumulation as a result to the high water velocity. The slope raster map was generated using DEM, and the *Slope* tool is ArcGIS software.

- Rainfall (R)

More heavy rains are more likely to result in flood and especially flash floods (Few et al. 2004). This study used annual maximum daily precipitation data for the period 1966–2019 for 13 gauged stations in El-Ham watershed. The maximum of each AMDP station data is then calculated and organized in the Attribute table in ArcGIS. The inverse distance weighted (IDW) technique allowed the precipitation distribution map to be plotted using the *IDW* Tool in ArcToolBox (Fig. 2).

- Land use/cover (LULC)

Seepage and runoff are dependent on land use/cover type. As defined in the literature, forest, glaciers, rivers, and bare soil or rocks are among significant factors (Cihlar and Jansen

2001). Land use/cover features are generated by man, such as buildings and roads in an urban area.

The existing land cover classes of the area are then reclassified into five groups according to their susceptibility to flood risk and ranked from 1 to 5 according to their impact on flooding.

- Soil type (ST)

El-Ham watershed constituted of many and different soil types according to FAO-UNESCO, 1974. The majority of its area contains Haplic Xerosols (Xk) in the center and southwestern parts, lithosols (l) are largely found in the north whereas calcic and haplic Yermosols (Yk and Yh) moved from the center toward the east parts. Xk can be described by low organic matter levels, wind erosion and the concentration soluble salts. Yk and Yh characterize by even drier climate than Xk. Finally, lithosols are fine soils composed of weathered rocks and calcic Cambisols (Bk) exist in the north but rarely found (Belazreg 2023).

3.3 Flood risk mapping

Risk for a natural disaster event is defined as the mathematical product between vulnerability and danger, which refers to the expected loss from a particular element at risk (Dall'Osso et al. 2006). Flood risk assessment is performed by flood hazard zoning and the sum of vulnerabilities derived from various vulnerability indicators (Danumah et al. 2016; Shivaprasad et al. 2017). The flood risk factors are considered in the flood hazard map and the population density map preparations. The flood risk map is obtained by a spatial layer overlay tool with ArcGIS software (Eq. 4). Five risk classes are defined to classify the sub-basin according to various risk severity zones ranging from high to low (Musungu et al. 2012; Elsheikh et al. 2015).

$$\mathrm{FRI} = (\mathrm{FHI} * W7) + (\mathrm{PD} * W8) \tag{5}$$

where FRI is flood risk index, FHI is flood hazard index, PD is population density parameter, and W7 and W8 are the appropriate weight parameters.

- Population density

Population density data correspond to Algerian census as the number of people per square kilometer square. Based on the Algerian districts map, districts constituting El-Ham watershed were retrieved using the *Clip* tool, and the density data were then introduced in the attribute table in ArcGIS software. The final map is obtained using IDW tool to interpolate population density data for the whole sub-basin and reclassified into five classes ranging from very low (value 1) to very high (value 5) depending on overflow sensitivity.

4 Results

All maps in the section below are determined using ArcGIS 10.4.1 software. The resulting maps are then reclassified on scales from 1 (very low) to 5 (very high) using the Reclassify tool in ArcToolBox (Sort method) (Rothman et al. 2013; Asare-Kyei et al. 2015; Rimba et al. 2017; Mokadem et al. 2018).

4.1 Criteria weighting results according to AHP technique

The determined weight for each of the six flood hazard factors is 39% for slope, 25% for drainage density, 18% for rainfall, 9% for elevation, 6% for land use/cover and 3% for soil type (Tables 2 and 3). To validate these outcomes, a consistency analysis has been performed. Here, the consistency index (CI) and the consistency ratio (CR) fell below 0.1 threshold value and indicate a high level of consistency, so the suggested weights are acceptable (Table 4). As there are six indices, the random index (RI) equals to 1.24 (see previous Table 1).

The importance intensity starting with 1 (equal importance), 3 (medium importance), 5 (strong importance), 7 (very strong importance), and 9 (extreme importance) can be used for 2, 4, 6 and 8 values to express intermediate values.

Table 2 Weights determination for each criteria using AHP method (where E: elevation; DD: drainage density; S: slope; R: rainfall; LULC: land use/cover; ST: soil type)

Pairwise comparison matrix						
Criterion	S	DD	R	E	LULC	ST
S	1	2	4	5	6	9
DD	0.5	1	2	4	5	8
R	0.3	0.50	1	2	8	7
E	0.2	0.25	0.5	1	2	6
LULC	0.17	0.20	0.125	0.5	1	5
ST	0.11	0.13	0.14	0.17	0.5	1
SUM	2.23	4.08	7.77	12.67	22.5	36

Table 3 Normalization of the pairwise comparison matrix values and determination of indices weights (where E: elevation; DD: drainage density; S: slope; R: rainfall; LULC: land use/cover; ST: soil type)

Normalization						
S	DD	R	E	LULC	ST	Weights
0.45	0.52	0.47	0.395	0.27	0.25	0.39
0.22	0.25	0.26	0.316	0.22	0.22	0.25
0.11	0.12	0.13	0.158	0.36	0.19	0.18
0.09	0.06	0.06	0.079	0.09	0.17	0.09
0.07	0.05	0.02	0.039	0.04	0.14	0.06
0.05	0.03	0.02	0.01	0.02	0.03	0.03
1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 4 Main results of consistency index and consistency ratio calculation

Parameter	Weighted sum vector	Consistency vector (CV)	λ	Consistency index (CI)	Random index (RI)	Consistency ratio (CR)
S	2.35	6	6	0	1.24	0
DD	1.49					
R	1.07					
E	0.55					
LULC	0.36					
ST	0.16					

4.2 Hazard assessment results in El-Ham watershed

The flood hazard layer is determined for precipitation, slope, drainage density, soil type, elevation and land use/cover layers using the Reclassification tool in the ArcToolBox in ArcGIS software (see Table 5 and Fig. 4).

The highest AMDP value (131.7 mm) is observed in the Central and North East of the sub-basin, and the lowest value (30.30 mm) is observed in the North-West of the Al-Ham sub-basin.

Slope analysis shows that medium slope values dominate the study area. Steep slopes are located in the north of the lower basin, others in the south (the highest value equals 43.61%), while lower slope values are located in the center of the El-Ham wadi. Surface runoff is slow in areas of gentle slope, allowing more time for rain water percolation. On the contrary, areas of steep slopes promote fast surface runoff allowing less residence time for rain water to infiltrate (Abdalla 2012).

The wadi (valley) is characterized by high drainage density values in regions with many streams. Drainage density is low in regions, where the streams are not numerous. Flooding is suggested to be high in cropland and herbaceous vegetation. According to the soil type description, flooding hazard is high in all regions except the northern regions.

The hazard map is shown in Fig. 5. The hazard map shows that the very dangerous area is located in the Center and North East of El-Ham wadi. Intermediate hazard spreads in regions of center, west and southwest with a great percentage.

4.3 Risk assessment results in El-Ham watershed

Figure 6 shows the flood risk map based on GIS and multi-criteria method. The flood risk layer can be made by following the same steps for the flood hazard layer. In addition to the flood hazard map (weighted equal to 66.66%), social vulnerability (weighted equal to 33.33%) is considered as the second major contributor to flood risk (Table 6). Population density can be seen high in Sour El Ghozlane (283.2 inhab/km^2), Chellalat El Adhaoura (185.7 inhab/km^2) and Sidi Aissa (113.5 inhab/km^2). The lowest densities are in Zerarka (12.01 inhab/km^2), Benzouh (13.68 inhab/km^2) and Birine (38.4 inhab/km^2) sub-areas.

The risk map shows a very high index in the central north-west and north-east of the study area. This map reveals that integrated risk is highest where the spatial density of the hazard and the population sensitivity overlap.

Rainfall-runoff inundation (RRI) model is a two dimensional model capable of simulating rainfall and resulting runoff and generate flood inundation (Sayama et al. 2012). In this study, the RRI model is applied to simulate El-Ham river and quantify the effect of upstream flood inundation on streamflow discharge in addition to its peak flow on the outlet of El-Ham watershed. Results for the application are presented in Fig. 7. Same annual maximum daily precipitation (AMDP) data have been introduced in the RRI model in order to obtain these results. Figure 7 shows that the peak streamflow in El-Ham watershed reaches almost 1750 /s which approximately is the same as the historical and observed values recorded and estimated by previous researches as (Hasbaia and Adoui 2015; Bendjeddou 2013). The graph in the same figure shows that flood water level corresponding to peak streamflow reaches 4.8 m at the outlet.

Table 5 Contributed parameters to flooding hazard in El-Ham wadi (R: rainfall distribution, S: slope, DD: drainage density, LULC: land use/ land cover)

Flood hazard mapping parameters							
Classification	Level	R (mm/day)	S (%)	DD (km/km^2)	LULC	ST	E
5	Very high	105.46–131.70	15.74–43.61	0–0.23	Built-up	Yh	1123–1799
4	High	87.56–105.46	9.56–15.74	0.23–0.40	Cropland	Yk	909–1123
3	Medium	72.85–87.56	5.13–9.56	0.40–0.56	Herbaceous vegetation	Xk	748–909
2	Low	54.56–72.85	2.05–5.13	0.56– 0.73	Bare/spare vegetation	Lithosol	614–748
1	Very low	30.30–54.56	0– 2.05	0.73–1.18	Shrubland	Bk	432–614

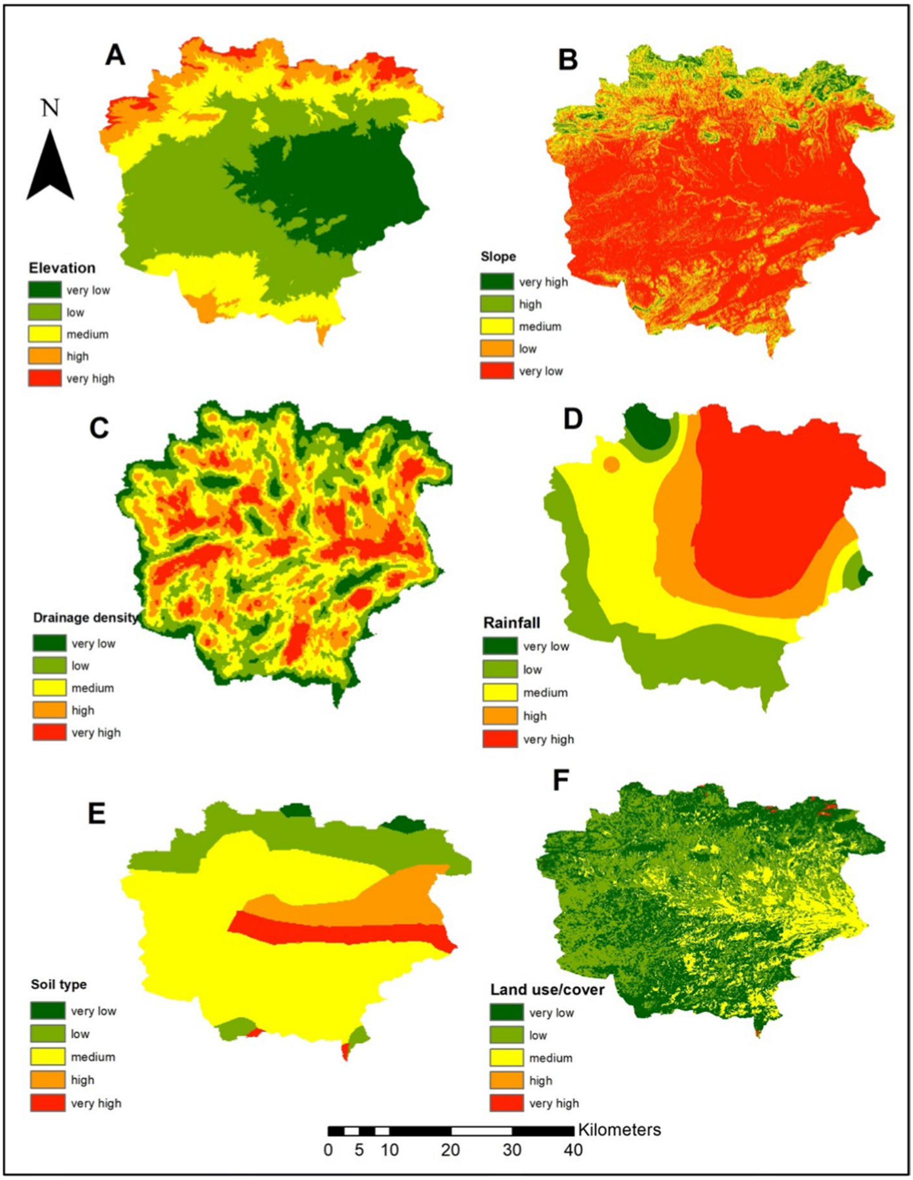

Fig. 4 Distribution of flood disaster for different indices: **a** elevation index; **b** slope index; **c** drainage density index; **d** annual maximum daily precipitation (AMDP) index; **e** soil type index and **f** land use/cover index

4.4 Discussion

This study considered the slope, the drainage density and the maximum daily precipitation as the three most important indices for flood risk mapping and in the weighted overlay process. El-Ham watershed flood risk was evaluated using multi-criteria analysis

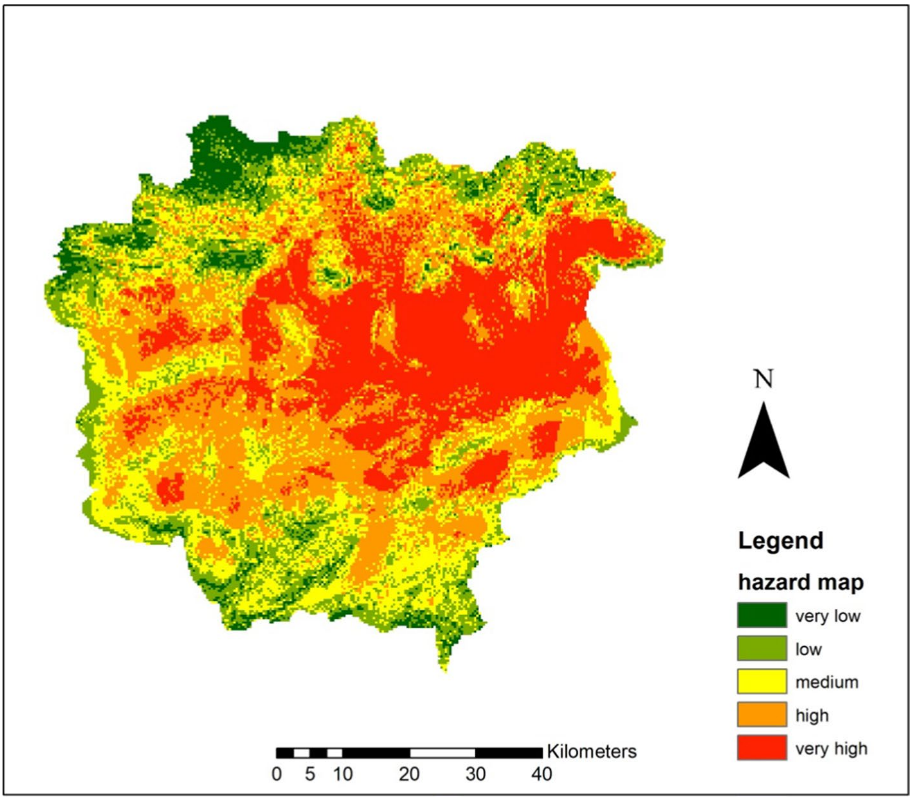

Fig. 5 Flood hazard map of El-Ham wadi

(MCA) approach, particularly analytical hierarchy process (AHP). The AHP technique combines both hazard and social index to obtain flood risk map. Each of the hazard-forming factors and risk-forming factors were reclassified into five classes from the very low to the very high susceptibility to flooding. The analysis shows that 57% of the El-Ham wadi falls between the very high to high risk of flooding, especially in the center, north and north-eastern parts of the El-Ham watershed.

Flood risk assessment is a useful tool to identify areas that are safe and non-safe for urban development (Hu et al. 2017). For this reason, establishment of a flood risk map is necessary for land use planning, for mitigation of flood disaster losses and risk reduction measures. However, risk assessment may not fully express the situation and may include several uncertainties. The choice of indices and their order are influenced by human experience; the lack of long-term maximum daily precipitation data and socio-economic statistics are some of these uncertainties.

AHP technique is one the many multi-criteria analysis methods which has facilitated the combination and overlaying of different factors. Results indicate that the AHP technique is very effective in assessing the hazard and risk of flooding integrated with GIS environment. Moreover, normalization, weighting and consistency analysis procedures can help reduce biases and uncertainties in the final outcomes.

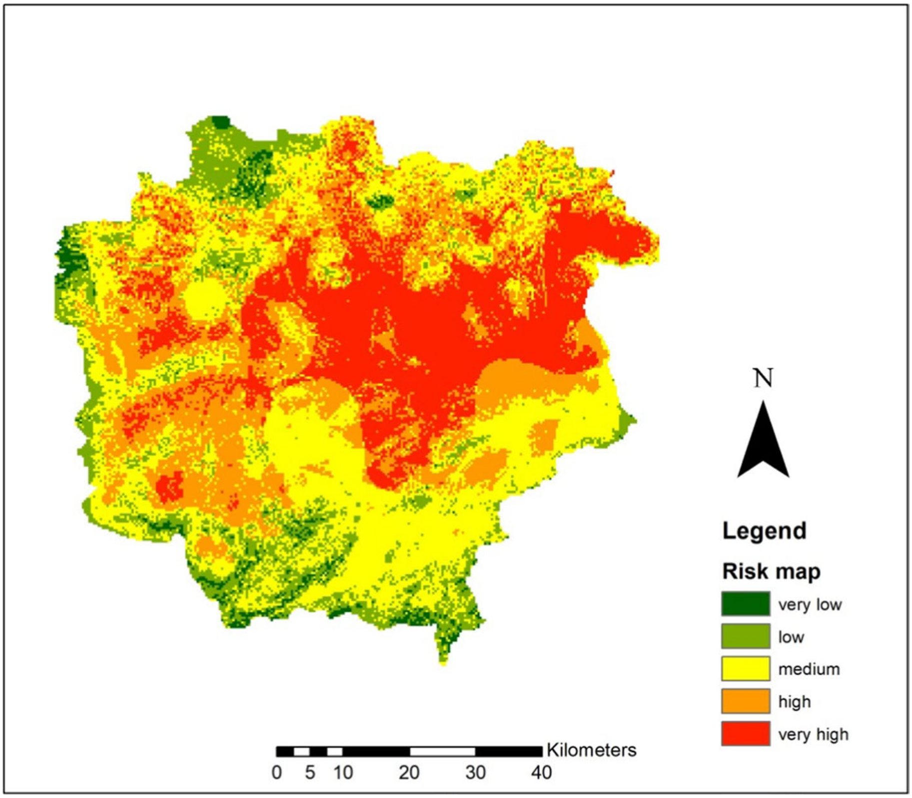

Fig. 6 Flood risk map of El-Ham wadi

Table 6 Social vulnerability contributing to flooding risk (PD: population density)

Classification	Level	PD (Inhabitants/km^2)
5	Very high	113.04–283.20
4	High	74.76–113.04
3	Moderate	49.23–74.76
2	Low	24.77–49.23
1	Very low	12.01–24.77

5 Conclusions

Flood risk is the probability of a flood event with actual damage (Rothman et al. 2013; Şen 2018). Flood risk mapping is a valuable tool for predicting flood risk prone areas and it helps water resource planners and decision makers focus on specific areas to make a more detailed assessment of flood risk.

The present study aims to assess the flood hazard and risk in the El-Ham watershed of the large Hodna basin (Algeria). It is based on the use of AHP and GIS. Six impacting indices were selected as necessary for flood risk assessment, namely slope, drainage density, rainfall,

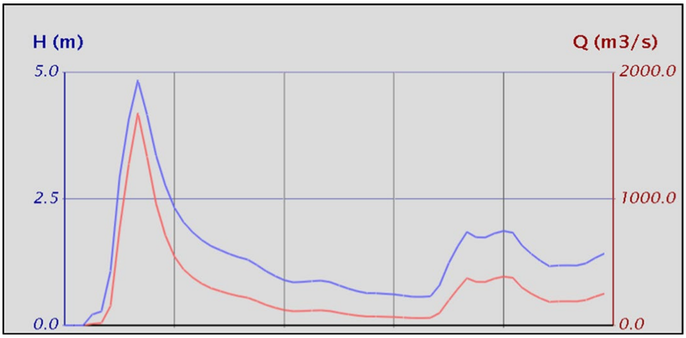

Fig. 7 Streamflow discharge and flood water height in the El-Ham watershed

elevation, land use/cover and soil type. The El-Ham wadi study area, a sub-basin in Algeria's Hodna basin, presents a high flood potential, especially in the North-Eastern, North-Western and Central part of the study area. However, this high potential decreases further when one goes toward the South. Further validation is required for the modeling, but the results obtained in this study are considered validated as no previous flood risk maps have been available for the El-Ham wadi area.

Strict measures are recommended in areas at risk of flooding to prevent greater damage and minimize the likely adverse impacts of floods on lives and livelihoods. Moreover, building flood alarm system and emergency response and escape plan is highly important and necessary for sustainable flood risk management.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

Consent to participate The authors voluntarily agree to participate in this research study. The authors had the purpose and nature of the study explained to them in writing and they have opportunity to ask questions about the study.

Consent for publication The authors warrant that the work has not been published before in any form except as a preprint, that the work is not being currently submitted to and is not under consideration by another publisher, that the persons listed above are listed in the proper order. The authors also warrant that the work does not libel anyone, infringe anyone's copyright, or otherwise violate anyone's statutory or common law rights.

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