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FLOOD RISK ASSESSMENT IN ARID REGIONS BASED ON HYDRAULIC MODELING WITH HEC-RAS. CASE STUDY OF WADI TAMDA IN DOUCEN, ALGERIA

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ABSTRACT

Flooding is widely recognized as one of the most extensive and destructive natural disasters on a global scale. Evaluating these flood hazards is crucial in the context of urban planning, land development, and hydrological analysis. Countries with arid climates pose a significant risk of flooding due to factors such as heavy rainfall, rapid urbanization, dry and infertile soils, and insufficient drainage systems. The study was conducted in the Wadi Tamda watershed, situated in the Doucen wilaya of Ouled Djellal, Algeria. The Wadi Tamda watershed is distinguished by the occurrence of swift inundation shortly after the initiation of rainfall. The objective of this study is to determine the locations that are susceptible to flooding, specifically those that experience floods with return periods of 10, 20, 50, and 100 years. In addition, we aim to create flood maps for extreme flood events in the region. This methodology has the potential to enhance the evaluation of flood vulnerability risk in the designated region. The methodology employed the HEC-RAS 2D model to simulate the hydraulic flow in the watercourse, considering various flow and boundary conditions. The simulation results were subsequently exported and analyzed using the Google Earth Engine software to generate flood maps. The risk maps indicate that the majority of the agricultural regions and a developed section of the secondary settlement of Khafoura, as well as the town of Doucen, are situated within a flood zone that poses a significant risk.

Keywords: Flood risk; Wadi Tamda; HEC-RAS 2D; Google Earth Engine, Doucen.

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INTRODUCTION

Natural hazards encompass a broad spectrum of potential threats originating from natural phenomena such as climate change, resource depletion, and geological events, with potentially disastrous consequences (Buhr, 2023). Among these, flash floods pose significant risks, especially in desert regions where rapid urbanization compounds their impact (Remini, 2023). These floods have historically had significant implications for individuals and communities, including loss of life, damage to homes and infrastructure, crop devastation and disruption to social affairs as well as livestock losses (Benkhaled et al., 2013; Mehta et al., 2020; Hafnaoui et al., 2023; Gohil al., 2024). However, in some areas flooding may rarely have a beneficial effect (Remini, 2022). Desert cities, due to their inherent environmental and climatic conditions, are particularly susceptible to such hazards (Derdour et al., 2017; Baudhanwala et al., 2023; Abd Rahman et al., 2023; Ben Said et al., 2024; Mah et al., 2024). The interplay between urban expansion and arid climates tends to exacerbate flood risks by altering hydrological patterns, increasing peak flow rates, and reducing the time to peak flows (Nezzal et al., 2015; Jeong, 2019; Benslimane et al., 2020; Helmi et al., 2022; Aroua, 2023; Nakou et al., 2023). This study is timely and innovative as it addresses these challenges, focusing on a region where traditional urban planning and flood management practices struggle to keep pace with the rapid changes brought by urban sprawl (Kouadio et al., 2018; Cherki, 2019; Nassa et al., 2021; Gassi and Saoudi, 2023).

The implications of urbanization on flash floods, especially in arid regions, have been well-documented, showing that even slight changes in land cover can significantly amplify the magnitude of flash floods and their potential damage (Bdour, 2022). The specific case of rapidly urbanizing desert cities highlights a critical need for modernized flood management systems, as traditional drainage infrastructures often prove inadequate under these changed conditions (Rözer et al., 2023). Yet, much of the existing research has been limited to broader urban contexts, without sufficiently addressing the unique characteristics of desert watersheds. This study aims to fill that gap by focusing on the nuanced interactions between climate variability, urbanization, and hydrological responses in arid environments.

Flooding poses significant risks to human life, infrastructure, and the environment, leading to economic losses, displacement, and waterborne diseases. Effective flood management is crucial to protect communities, ensure the resilience of urban and rural areas, and safeguard water resources. With climate change increasing the frequency and intensity of floods, proactive measures such as improved drainage systems, risk mapping, flood control reservoirs, flood risk strategies, dry stormwater detention pond, early warning systems, and sustainable land use planning are essential to mitigate damages and enhance disaster preparedness (Ayari et al., 2016; Bouly et al., 2019; Hountondji et al., 2019; Bekhira et al., 2019; Aroua, 2020; Remini, 2020a; Remini, 2020b; Remini, 2020c; Remini, 2020d; Bentalha, 2023; Zegait and Pizzo, 2023).

Flood protection, flood forecasting and reservoir operation are closely linked, as reservoirs play a crucial role in regulating water flow and mitigating flood risks. By strategically controlling the storage and release of water, reservoirs help prevent downstream flooding during heavy rainfall or extreme weather events. Effective reservoir operation ensures that excess water is retained during peak inflow periods and gradually released when the risk of flooding subsides. Properly managed reservoirs not only protect communities and infrastructure from flood damage but also support water supply, irrigation, and hydropower generation. This critical aspect of the problem holds great significance and is thoroughly examined in the following relevant references (Cherki, 2019; Mezenner et al., 2022; Mehta et al., 2023; Verma et al., 2023; Trivedi and Suryanarayana, 2023: Shaikh et al., 2024).

In Algeria, flash floods are the most common type of flooding, resulting in significant loss of life and damage to infrastructure, highlighting the urgent need for improved and adaptive flood management strategies (Boudani et al., 2020). The arid regions of Algeria, with their erratic rainfall patterns and poor watershed management practices, face heightened flood risks. Issues like low soil permeability and inefficient drainage systems further aggravate this situation, making flood management in these areas particularly challenging**.** Prior studies in regions such as the M'zab Valley and Bou Saâda wadi sub-basin have mapped flood risks, identifying zones of varying vulnerability (Rezaei-Sadr and Eslamian, 2022; Abdelkrim et al., 2023). However, the Wadi Tamda watershed in Doucen, characterized by its unique climatic, geological, and hydrological profile, remains underexplored. This study addresses this research gap by providing a detailed analysis of flood risks in the Wadi Tamda watershed, utilizing advanced hydraulic modeling and GIS-based approaches.

The Doucen region in western Zab is particularly known for its vulnerability to flash flooding, primarily due to extreme rainfall events (Djennane, 2016). A case in point is the severe flooding event in September 2009, where more than 60 mm of rainfall fell within 48 hours—surpassing the estimated annual average of 82 mm—resulting in the overflow of Wadi Tamda and prolonged flooding over nearly a week (Hafnaoui et al., 2020). Despite such events, there remains a critical need for a robust, scientific approach to flood risk assessment in the area, which can guide decision-making and improve local flood preparedness.

This study aims to comprehensively assess the flood risk in the Wadi Tamda watershed in Doucen by integrating climatic, morphological, lithological, and structural data with advanced hydraulic modeling and flood simulation techniques. This approach is novel in its detailed incorporation of GIS tools and HEC-RAS hydraulic modeling for simulating flood scenarios, mapping water erosion, and quantifying the potential impact of various factors on flood dynamics. While previous studies have applied hydraulic modeling and GIS techniques in arid regions (Abd Rahman et al., 2016; Abdessamed and Abderrazak, 2019; Helmi et al., 2022), this study distinguishes itself by focusing on the underrepresented Wadi Tamda watershed and developing a detailed spatial analysis that includes both risk mapping and the simulation of potential mitigation measures.

HEC-RAS has the ability to calculate the water surface profiles for steady and gradually varied flow as well as for subcritical, supercritical, and mixed flow regimes (Kumara and Mehta, 2020). The integration of GIS with HEC-RAS allows for the creation of precise flood risk maps that identify high-risk urban areas and potential vulnerable zones. These maps serve as a critical tool for local decision-makers, enabling them to implement effective flood management interventions tailored to the specific conditions of the region. The outcomes of this study are expected to contribute significantly to local flood risk management practices by offering actionable insights into the spatial distribution of flood risks and by providing a model that can be adapted to similar arid regions facing comparable challenges. Hydrodynamic models are reliable tools for urban stormwater management. The scientific planning and design of urban drainage systems, as well as the development of effective urban flood control and management strategies, depend on numerical simulations of urban flooding (Gangani et al., 2023), with the prediction of these models mitigating the effects of extreme weather conditions and ensuring community safety (Mehta and Kumar 2022; Mehta et al. 2022, Baudhanwala et al., 2024). This research not only aims to mitigate the consequences of flooding but also seeks to inform policies that can prevent future flood events, thereby saving lives and minimizing property damage.

STUDY AREA

The Doucen region is situated in western Zab, 80 kilometers from Biskra and 20 kilometers from the Ouled Djalal Wilaya. It is located between longitudes 4.57° and 5.17° and latitudes 34.30° and 34.45° north, covering an area of 642 km2 (Fig. 1). The area is a plain with elevation and undulation that expands from north to south and east to south-west. The height decreases to around 50 m on the south-west side, which corresponds to the elevation decrease in the Saharan Atlas Mountains. Because of the abundance of main and secondary watercourses, the desert plain and Doucen plain are primarily regarded as flood plains. Doucen is geomorphologically located at the southern foothills of the Saharan Atlas Mountains range, which limits the commune’s north with a mountainous area of sometimes fairly rugged relief and difficult access, as well as a slightly sloping area of relief, forming a basin in the south. The plains cover almost the entire commune of Doucen and are distinguished by alluvial soils from several wadis that cross the region (Khadraoui, 2011), hence the name alluvial plains.

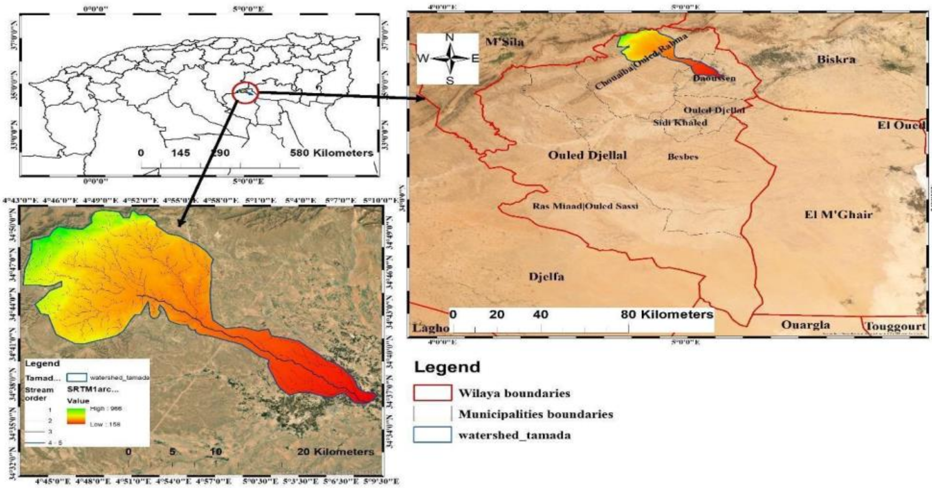

Figure 1: Location map of the study area

Hydrographic network

The Wadi Djedi watershed covers 24,200 km². It is the most significant stream in the Chotte Melghir watershed (Chabour, 2006). Wadi Djeddi can be considered the collector of the vast gutter that stretches over 500 kilometers at the foot of the Saharan Atlas (Dubief, 1953). The tributaries of Wadi Doucen contribute to the Wadi Djeddi watershed. The main wadis that cross the Doucen region are Wadi Tamda, Wadi Khafoura, and Wadi Doucen (Fig. 2).

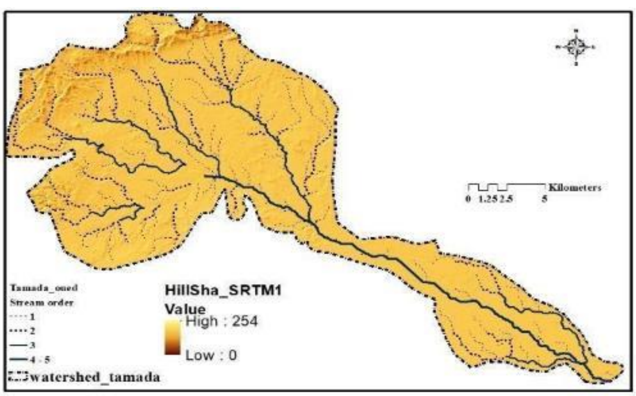

Figure 2: Hydrographic network and topography of the study area

MATERIAL AND METHODS

Calculating the population growth rate

The population growth rate is a metric used to calculate the average annual increase in population over a specific timeframe, presented as a percentage. Equation (1) can be utilized to compute the population growth rate (P.R.B, 2024):

$$R = ln\left(\frac{P_2}{P_1}\right)T \times 100 \qquad (1)$$

where, R is the population growth rate, P_2 is the ending population, P_1 is the starting population, T is the time interval in years between the starting and ending populations, and Ln is the natural logarithm. The future population of the town of Doucen was estimated for 2035 and 2050, by applying the following equation (2):

$$P = P_0(1 + X)_n \qquad (2)$$

where, P is the projected population, P_0 is the population in reference year (P_0 = 11389 in 2008), X is the growth rate, and n is the number of years in the time interval under consideration. We set this rate of increase to be equal (X=2.3%) across different study horizons.

Climate variability study

The meteorological data used in this study were sourced from (NASA Power, 2024). These are primarily monthly rainfall series from Doucen from 1982 to 2023. The data were used on an annual basis to calculate the Standardized Precipitation Index (SPI). SPI is a popular tool for assessing and monitoring drought conditions and uses a probability distribution function of precipitation to identify drought events and their severity based on their deviations from long-term average precipitation. SPI is classified as a reduced-centered variable and is calculated using the following Eq. **(3)** (Kraus, 1977; Lamb, 1995):

$$SPI = \frac{(X_i - X_m)}{\sigma} \qquad (3)$$

X_i is the rainfall in year I, x_m is the average interannual rainfall over the reference period, and σ is the standard deviation of interannual rainfall over the reference period.

The extent of a drought episode is determined by adding the indicator values for all months of the drought. Index values greater than 2.00 are considered very wet, while values less than -2.00 are considered extremely dry. Table 1 shows values ranging from 0.99 to -0.99, indicating more or less normal conditions. The SPI's coverage period will thus vary depending on the type of drought being analyzed and applied: for example, the SPI will cover 1 to 2 months for a meteorological drought, 1 to 6 months for an agricultural drought, and 6 to 24 months or more for a hydrological drought (W.M.O, 2012).

Table 1: Classification of drought according to SPI values (McKee et al., 1993).

SPI	>2	1.50-1.99	1.00-1.49	0.50-0.99	-0.49-0.49
Class	Extremely wet	Very wet	Moderately wet	Mildly wet	Normal conditions
SPI	-0.50--0.99	-1.00--1.49	-1.50--1.99	<-2.00	-0.50--0.99
Class	Mild drought	Moderate drought	Severe drought	Extreme drought	Mild drought

Hydraulic modeling

The HEC-RAS model is widely used in hydraulic modeling because it takes a physics-based approach to studying storm runoff. Hydraulics modeling provide a better understanding of the depth and extent of water flow in each zone, as well as the location and timing of runoff slopes (Kumar et al., 2023). Numerous case studies in similar contexts have supported its validity (Yalcin, 2020). This study focused on predicting runoff, which is critical for early flood warning. The Hydrologic Engineering Center-River Analysis System (HEC-RAS 5.0.4) is an open-source hydraulic flow analysis program created by the United States Army Corps of Engineers' Hydrologic Engineering Center (HEC-RAS, n.d.) (Zainalfikry et al., 2020). The HEC-RAS model is suitable for both 1D and 2D modeling, One-dimensional (1-D) hydraulic models are used to forecast the floods and water levels in the river and floodplain (Mehta et al., 2020). This study makes use of a simplified two-dimensional flow model to assess the hydraulic efficiency of various adaptation strategies. The research methodology for HEC-RAS software modeling includes the following steps:

Hydrological study

First, the physical and hydromorphometric characteristics of the watershed are investigated, as these are the foundation of all hydrological studies (Grecu, 2018). to enable this, In this case, the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), characterized by a 30-meter resolution and acquired from the United States Geological Survey (USGS, 2024) Earth Explorer website, then processed in Google Earth Engine (GEE, 2024) environment to extract the various maps of a slope, hypsometry and hydrographic network to calculate the morphometric parameters of the catchment area (surface, slope, average altitude, length of the main talweg, etc.). Digital elevation models are commonly used to analyze topographic features (Meadows et al., 2024). A digital elevation model is a regular network of cells, with each cell representing a specific elevation value. This basis is used in hydrological studies, such as flood studies, to determine the water drainage network and basin boundaries, as well as in a few other applications, such as hydraulic modeling.

It is followed by a statistical analysis of peak rainfall over 41 years (1982-2023) (NASA Power, 2024). The data was statistically analyzed using the Hydrological Frequency Analysis Plus (HYFRAN Plus) software. It can be used to fit a large number of statistical distributions to a set of data observations and test hypotheses such as independence, homogeneity, and stationarity. The normal, lognormal, and Gumbel distributions were used to investigate flood frequency, the Gumbel's distribution represents an enormous value from a reasonably large group of independent values from distributions with relatively rapidly decaying tails, such as exponential or normal distribution (Mangukiya et al., 2022). IDF curves (intensity, duration, and frequency curves) were then generated to depicts the evolution of rainfall intensity as a function of duration and frequency, as expressed in return periods. The process of developing IDF curves is critical in water risk management and prevention. Flood concentration and peak flow times are then calculated using empirical formulas for various return periods (Table 2).

Table 2: Summary of formulas used in this study

Statistical data analysis	Normal laws	$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}$	$\mu = 21.1544$ $\sigma = 9.94677$
	Lognormal laws	$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} exp\left\{-\frac{[\ln x-\mu]^2}{2\sigma^2}\right\}$	$\mu = 2.93342$ $\sigma = 0.509847$
	Lois Gumbel	$f(x) = \frac{1}{\alpha} exp\left[\frac{-x-u}{\alpha} - exp\left(\frac{-x-u}{\alpha}\right)\right]$	$u = 2.93342$ $\alpha = 0.509847$
IDF curves	Short-duration rains	$P_{tc} = P_{max/j}\left(\frac{t}{24}\right)^b$	Pmax/d: Maximum daily rainfall; t: Duration in hours; b: Climatic exponent (b=0.38 given by National Water Resources Agency (NWRA)). Ptc: Short-term rainfall (mm) ;
	Maximum intensity duration t(h)	$I_t = \frac{P_{tc}}{t}$	
Concentration time	Giandotti formula	$T_c = \frac{1.5L + 4\sqrt{S}}{0.8\sqrt{H_{moy} - H_{min}}}$	S: catchment area in Km²; L: length of main embankment in Km; Hmoy, Hmin: respectively the mean and minimum height of the B.V in m; C: runoff coefficient for the flood considered with probability P%; F: hydrograph shape coefficient; α: runoff coefficient for the probable flood.
Flood study	Turazza formula	$Q_{max.p\%} = \frac{C * P_{tc} * S}{T_c * 3.6}$	
	Sokolovsky formula	$Q_{max.p\%} = \frac{0.28 * P_{tc} * \alpha * F * S}{T_c}$	
Flood hydrograph	The rise of the flood	$Q_m(t) = Q_{max.p\%} * \left(\frac{t}{t_m}\right)^3$	$Q_{max.p\%}$: Maximum (peak) flood flow (m3/s). t_m: Rise time (h). - t_d: descent time (h). - t_b: Base time (h).
	The recession	$Q_t(t) = Q_{max.p\%} * \left(\frac{t_b - t}{t_d}\right)^3$	

The HEC-RAS software

The HEC-RAS software is used for hydraulic modeling and is the most widely used flood simulation program. This model assesses water level and velocity in rivers, i.e., 1D and 2D unsteady flow, as well as sediment transport, moving bed, water temperature, and quality (AL-Hussein et al., 2022). In this study, HEC-RAS version 6.4.1 was used to simulate unsteady flow data for the Doucen flood over selected return periods. This study used the two-dimensional (2D) HEC-RAS model to simulate and map flooding. HEC-RAS 2D employs shallow water equations to explain water movement using depth-averaged 2D velocity and water depth. Djafri et al (2024) mentioned that the 2D model is one of the popular models, which has been increasingly used in the last few years. In addition, it works better to solve complex immersion operations in urban landscapes due to its capability of simulating lateral unsteady flow dynamics, including backflow in floodplains. Several critical processes are carried out during 2D hydraulic modeling using HEC-RAS to obtain accurate floodplain mapping and risk assessment (El-Bagoury and Gad, 2024; Pandit and Bhattarai, 2023).

Topographic accuracy is crucial in two-dimensional hydraulic modeling applications (Leitão and De Sousa, 2018). We downloaded a digital surface model (DSM) with a resolution of 30 meters (Fig. 3a) downloaded from (ALOS, 2024). Numerous studies have demonstrated the effectiveness of this paradigm (Macchione et al., 2019). For example, in the El Bayadh region, researchers used a digital surface model to compare flood boundaries plotted by the El Bayadh municipality’s technical staff with those predicted by the HEC-RAS software, and the results revealed a fairly high degree of agreement (Hafnaoui et al., 2022). The next step in our research is to prepare the geometry, which entails drawing the boundaries of the flooded region in 2D.

The modeling process employed a mesh of 30 x 30 cells (Fig. 3b). Furthermore, the roughness coefficient is regarded as one of the most important factors in hydraulic applications, as it influences the extent of flooding. Several methodological approaches are suggested for calculating this coefficient. In this study, the roughness coefficient is calculated by combining the coefficient data with the Environmental Systems Research Institute 2021 (ESRI 2021) Land Use Land Cover (LULC) of the study area (Fig. 4). However, only geometry values were used in this study (Chow, 1959) (Table 3).

In addition, the flood hydrograph and normal depth boundary conditions were applied in two distinct ways. During the restored periods, the downstream end of Wadi Tamda was subjected to normal depth boundary conditions, while the upstream end were subjected to flow hydrography. Using finite volume techniques, the HEC-RAS software determines the middle of each digital cell for a given time step. The flood risk map is based on the Wadi Tamda topographic survey (Sunilkumar and Vargheese, 2017; Thapa et al., 2020). Hydraulic modeling makes use of hydrological flow data and stream geometry. Cross-sections are used to model the Wadi, as well as the longitudinal slope and roughness of the bed and banks at each calculation point.

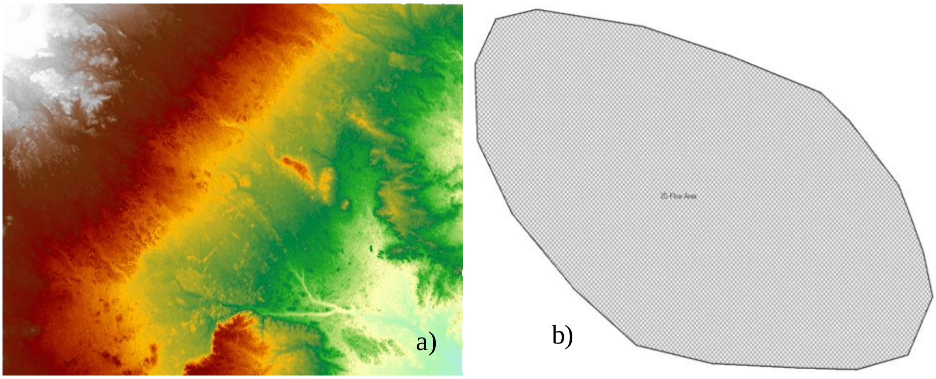

Figure 3: (a) Digital surface model (DSM) used, (b) 2D flow area and 2D mesh

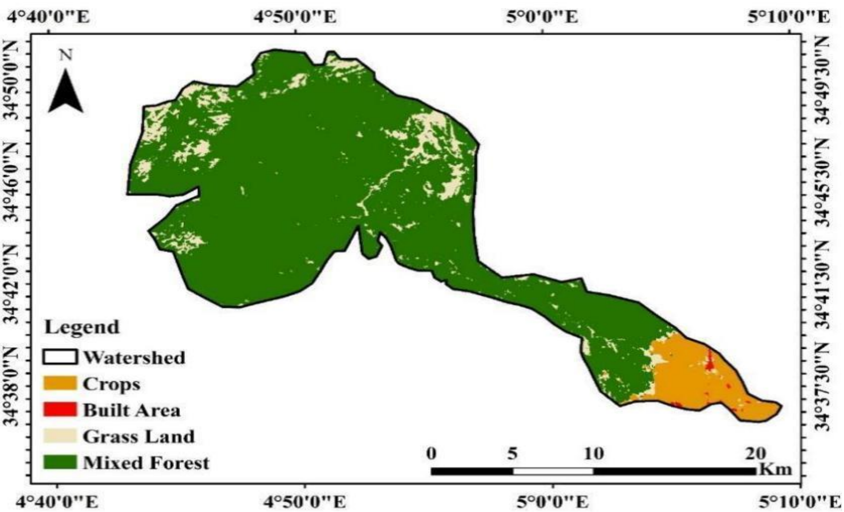

Figure 4: LULC map of selected case study

Table 3: Study area for Manning's roughness coefficient based on ESRI 2021 LULC data

Labels	Manning's n
Mixed forest	0.12
Built Area	0.035
Grass Land	0.04
Crops	0.035

RESULTS AND DISCUSSION

Calculating the population growth rate

According to the 2008 general population census, the population of Doucen is 1,1389. The average annual growth rates recorded during the periods 1966-77, 77-87, 87-98, and 1998-2008 were 3.8%, 6.88%, 2.9%, and 2.3%, respectively. Population growth rates have followed irregular patterns. According to future population projections, the population will reach 29598 by 2050, more than doubling the 2020 figure of 14962. This growth is directly related to the development of the urban fabric, which is concentrated near the banks of the Wadis in the Doucen region, on the one hand, and the agricultural dynamism that characterizes the commune and has made it an appealing territory for the population, on the other.

Table 4: Future population trends of the commune of Doucen

Year	Population	Year	Population
2008	11389	2030	18782
2010	11919	2035	21044
2015	13354	2040	23578
2020	14962	2045	26417
2025	16764	2050	29598

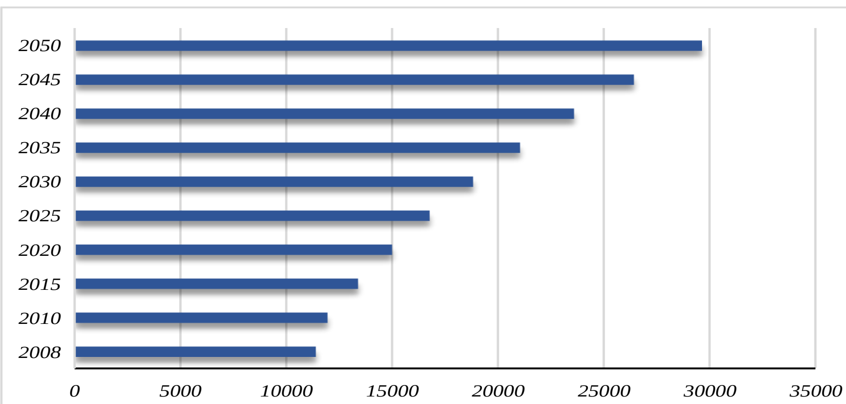

Figure 5: Projected population trends for the commune of Doucen up to the year 2050 based on data from the National Office of Statistics (N.O.S, 2011).

Future population growth in the commune of Doucen has been estimated up to 2050 (Fig. 5, Table 4), with the population doubling to around 2,958 by 2050. This demographic projection indicates a significant urbanization potential, which implies the transformation of rural areas into urban zones, hence the possibility of urbanization in flood-prone areas, particularly near the Wadi.

Climate variability study

Figs. 6 and 7 show significant trends in annual precipitation and mean monthly temperatures between 1982 and 2023. Annual precipitation is highly variable, with exceptionally wet years like 1982 and 2004 and a downward trend in recent years. Monthly maximum and minimum temperatures show a marked seasonal pattern, with high maximum temperatures in summer (July and August) reaching around 35°C and low minimum temperatures in winter (January and December) around 5°C. Thermal amplitude is lowest in the winter and highest in the summer, indicating an arid climate with significant seasonal variation. This variability could be influenced by global climate change.

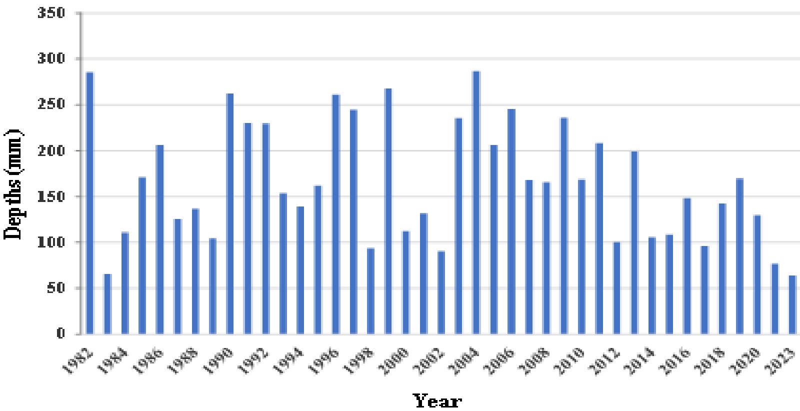

Figure 6: Annual rainfall from 1982 to 2023 (Data processed from source: NASA Power, 2024)

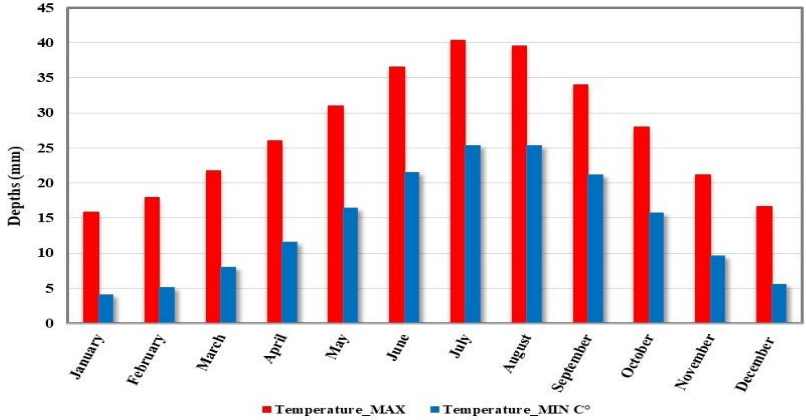

Figure 7: Average temperature from 1982 to 2023 (Data processed from source: NASA Power, 2024)

SPI is a tool for evaluating precipitation anomalies over time that has been used in a variety of sectors, including agriculture, hydrology, and water resource management. Rainfall variations in the Doucen region were analyzed using SPI indices calculated over 41 years, from 1982 to 2023. SPI values are represented by bars: blue bars indicate excess precipitation, corresponding to wetter conditions, and red bars indicate precipitation deficits, corresponding to drier conditions (Fig. 8). These four extended periods of low rainfall (1983-1984, 1987-1989, 2000-2002, and 2014-2023) can result in drought, soil degradation, and desertification. This has implications for vegetation, wildlife, and ecosystems. Following that, four periods of excessive precipitation, 1982, 1990-1992, 1996-1999, and 2003-2011, can cause flooding on a larger scale, damaging natural habitats, infrastructure, and farmland, such as the September 2009 floods, which submerged 164 houses, 9790 palm trees, 744 greenhouses, and 200 hectares of various crops. Floods and droughts are costly in terms of infrastructure repairs, humanitarian aid, and economic losses (Khalid and Ali, 2020).

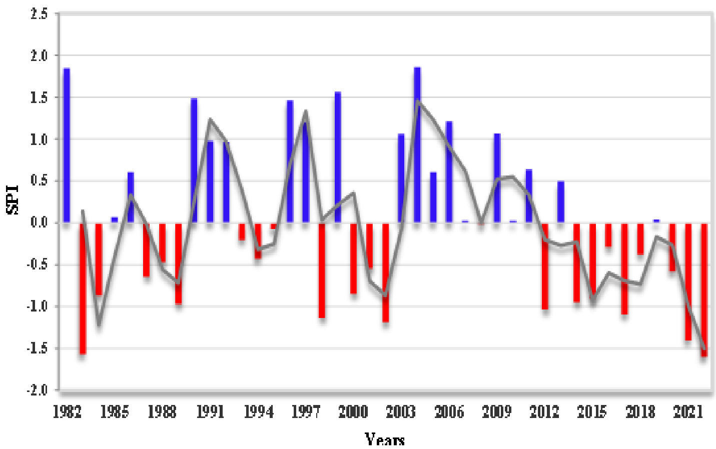

Figure 8: standardized precipitation index calculated on the basis of data from the 1982-2023 precipitation period at Doucen.

Hydraulic modeling

Hydrological study

The annual maximum daily rainfall in Wadis Tamda is critical for flood frequency analysis and hydrological modeling. Fig. 9 depicts the wide range of mean daily rainfall, from the lowest value of 5.16mm recorded in 1983 to the highest value of 39.66mm, which corresponded to the Doucen flood in 2009. The maximum daily rainfall for each year is statistically analyzed using the Hydrological Frequency Analysis Plus (HYFRAN Plus) software. Studies conducted in the region have focused on estimating the frequency of daily rainfall and determining the distributions of extreme values for various return periods, thereby contributing to the development of long-term flood mitigation measures (Aldrees, 2022).

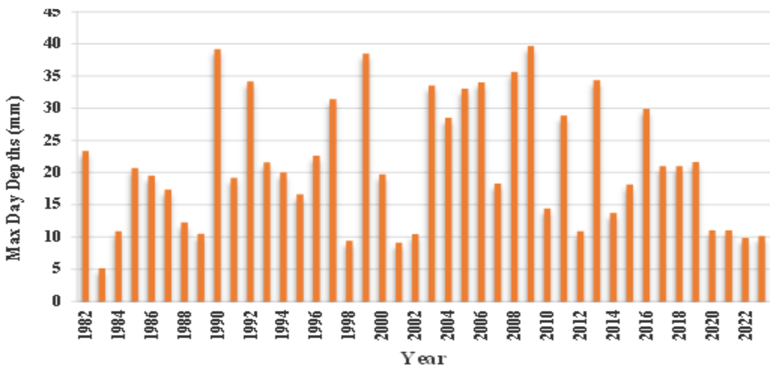

Figure 9: Maximum annual daily rainfall of Wadi Tamda from 1982 to 2023 (Data processed from source NASA Power ,2024)

After testing several statistical methods used in flood frequency analysis (exponential, GUV, gamma, Gumbel, normal, and lognormal), the 41-year peak flows of Wadi Tamda are consistent with the lognormal approach. This analysis should allow us to estimate the quantiles for the return periods chosen for this study: 2, 5, 10, 20, 50, and 100 years. This statistical method was used to calculate peak flows (Qmax) over various average return periods (Abdessamed and Abderrazak, 2019) (Table 5, Fig. 10).

Table 5: Statistical analysis of maximum daily rainfall Gumbel law, log normal

Model	No. of parameters	XT	P(Mi)	P(Mi | x)	BIC	AIC
Lognormal	2	61.542	25.00	44.12	308.082	304.655
Gumbel	2	54.187	25.00	39.79	308.288	304.861
Normal	2	44.298	25.00	9.49	311.154	307.727
GEV	3	50.045	25.00	6.60	311.883	306.742

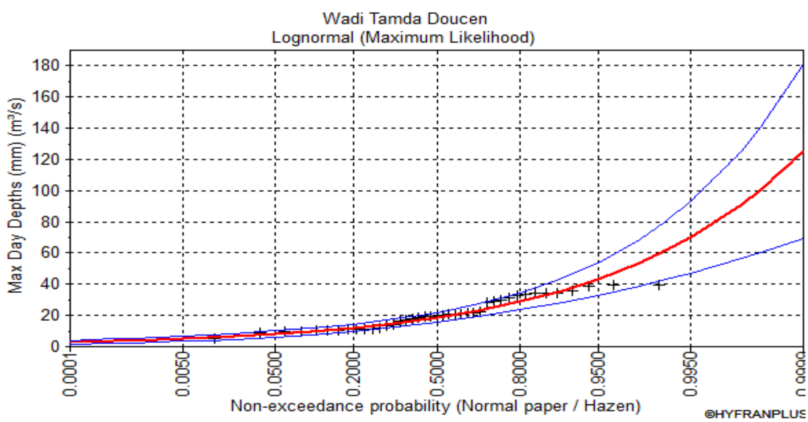

Figure 10: Adjustment of maximum daily flows to a Log normal distribution Doucen rainfall data processed by HYFRAN Plus software.

Fig. 11 depicts curves representing different precipitation return periods measured in years (5, 10, 20, 50, and 100 years, respectively). The curves show the relationship between rainfall duration and intensity over various return periods. These figures are useful for understanding and predicting rainfall intensity over various periods. They can be used to plan and design flood control systems or infrastructure that will withstand specific storm events.

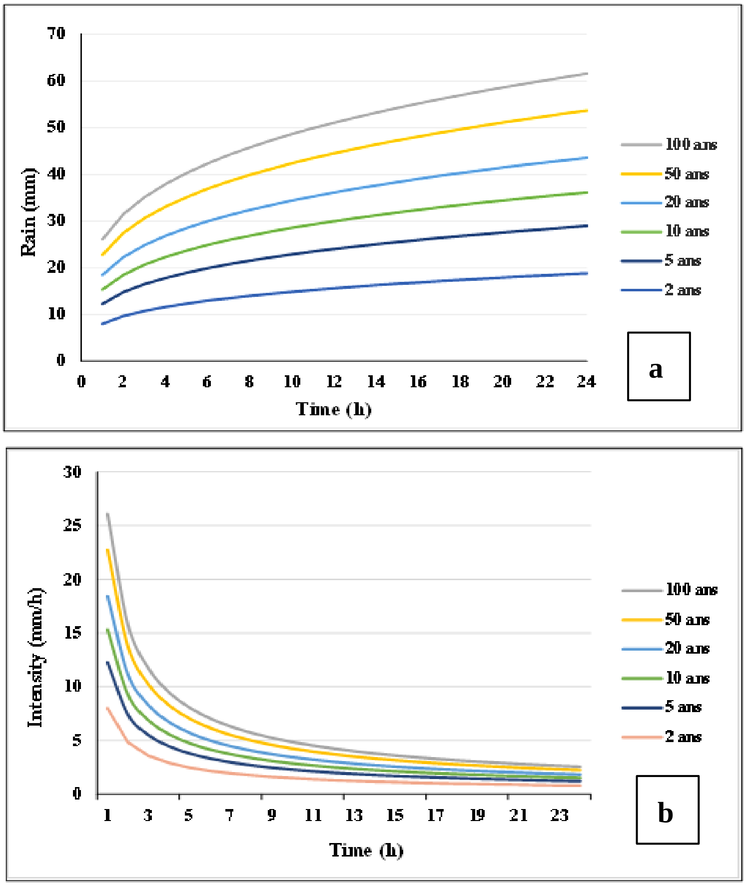

Figure 11: (a) Rain of short period; (b) Maximum intensity duration

Flood study

Slope analysis is critical to any hydrological study because it allows us to determine the type and characteristics of runoff, the type of rainwater runoff, the type of surface runoff, and the areas at risk of flooding. Fig. 12 shows that the Wadi Tamda watershed has low (>5°) and moderate slopes (5° to 10°). Low slope values indicate that runoff will be slow, and water stagnation and flooding may occur (Diawara et al., 2022). From the watershed's hypsometric curve (Fig. 12), we were able to estimate the overall slope index of the total watershed area (H5% - H95%) by the length of the equivalent rectangle (Laabidi et al., 2016) to calculate the time of concentration using Giandotti's formula, where the value is 9.59. The Turazza and Sokolovski formulas (Table 6) were used to calculate Qmax based on concentration time, short-duration rainfall, and maximum intensity duration.

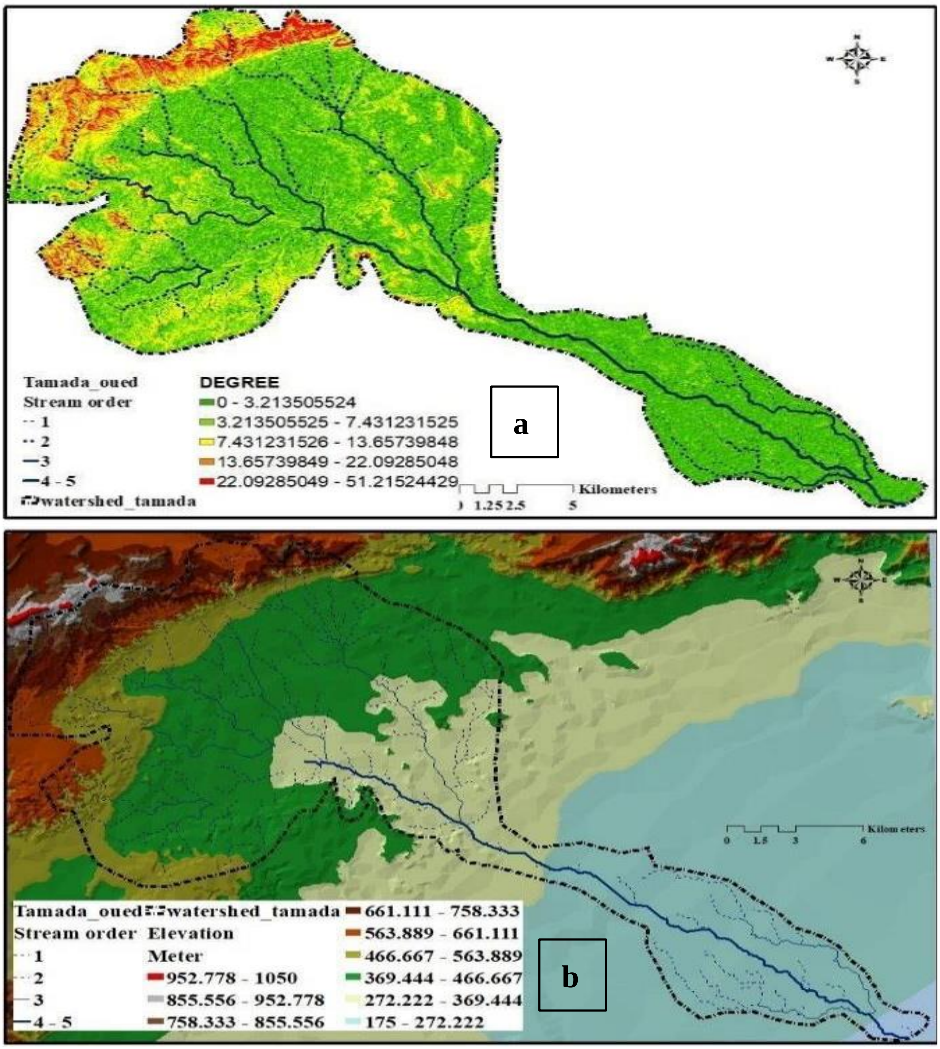

Figure 12: (a) Slope map; (b) Elevation in meters

Table 6: Maximum flood intensity at Wadi Tamda for return periods (Doucen rainfall data, NASA Power, 2024).

Return period	Pt	It	Qmax Turazza	Qmax Sokolovski	Average Qmax
100 years	56.12	6.96	605.994	312.80	459.40
50 years	49.37	6.13	501.807	255.56	378.68
20 years	43.03	5.34	410.013	205.60	307.80
10 years	34.92	4.33	310.570	152.95	231.76
5 years	28.98	3.60	239.327	115.39	177.36
2 years	23.20	2.88	176.857	83.14	130.00

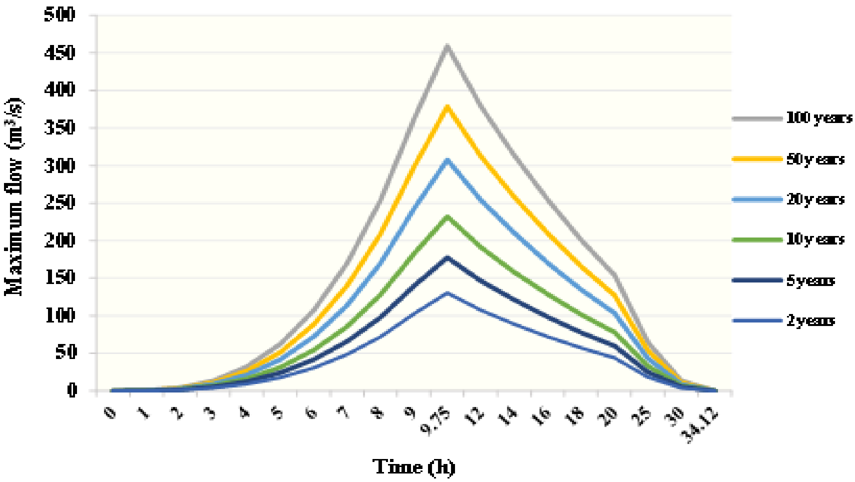

Figure 13: Flood hydrograph at Wadi Tamda for return periods

The flood hydrograph is an important tool for understanding a watershed's hydrological response to precipitation events, and it is determined by the mean Qmax values of the Return Periods. The figure depicts the flood hydrograph's asymmetrical bell shape. It is divided into four categories: drying up (before net rainfall), flooding, recession, and drying up. Urbanization has a significant effect on flood hydrographs. Urban areas and impermeabilized surfaces (roads, buildings, sidewalks) reduce groundwater infiltration, increasing surface runoff and causing flood flows. Urban floods are frequently faster and more intense due to direct runoff into waterways. Urban flood hydrographs may differ in shape from those of non-urbanized basins. They may have higher peaks and shorter durations (Fig. 13).

The physical characteristics of the Wadi Tamda watershed

The physical characteristics of the Wadi Tamda watershed slope, hypsometry, hydrographic network must be studied to calculate the morphometric parameters needed for our hydrological study and the study of fluvial dynamics. Furthermore, studies in Medina used models such as HEC-HMS to estimate flood hydrographs and peak flows based on daily rainfall distribution, emphasizing the importance of understanding maximum daily rainfall for effective Wadi corridor management in arid regions (Gunawardhana et al., 2015).

Table 7: Morphometric characteristics of the Wadi Tamda watershed Individual analysis of SRTM satellite imagery using QGIS software.

Morphometric parameters		Units	Wadi Tamda watershed
Area (A)		Km^2	368.652636
Perimeter (P)		Km	125.849257
Main Talweg Length (L)		Km	35.439
Compactness index (the GRAVILIUS capacity coefficient)		/	
Equivalent	Length (L)	Km	45.404929
Rectangle	Width (W)	Km	8.119220625
Elevation Characteristics	Elevation 5%	m	721
	Elevation 5%	m	800
Elevation Characteristics	Elevation 95%	m	310
	Maximum elevation (H_{max})	m	950
	Minimum elevation (H_{min})	m	175
	Average elevation	m	562.5
Overall slope index (Ig)		m/Km	96.27
Useful height difference (Du)		m	523
Specific height difference (Ds)		m	670.0747162
Watershed relief (R)		/	
Drainage density (Dd)		Km/Km^2	1.059638158

Hydraulic modeling

Several research studies have demonstrated the effectiveness of hydraulic modeling using the HEC-RAS program to assess flow depths and velocities during extreme rainfall events (Sunilkumar and Vargheese, 2017; Zainalfikry et al., 2020; AL-Hussein et al. 2022; Pandit and Bhattarai, 2023; El-Bagoury and Gad, 2024), which improves drainage systems and canal performance (Hassan et al., 2022). Furthermore, the HEC-RAS model has been instrumental in identifying flood-vulnerable areas and simulating flood scenarios to predict flooding extent, thereby aiding in prevention and control measures (Dorin et al., 2022; Razi et al., 2022). The results of this study's hydraulic models are presented as flood maps for various return periods. Fig. 14 depicts the observations across the various return periods examined. This similarity suggests that flood areas will increase over time, i.e., during the return period, as new branches emerge in the Wadi. This finding has significant implications for understanding the hydraulic dynamics of Wadi Tamda under changing hydrological conditions

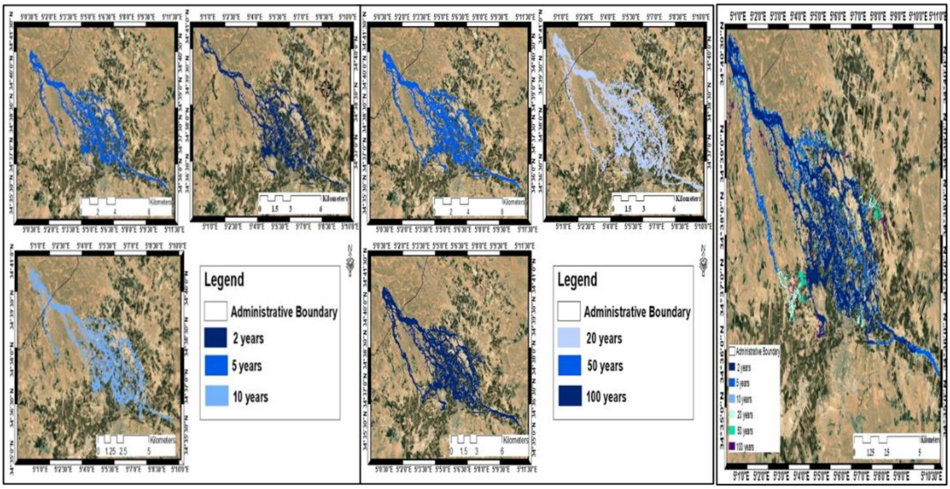

Figure 14: Wadi Tamda flood map return periods 2, 5, 10, 20, 50 and 100 years.

Table 8 summarizes the variation in water flow velocity for each return period and water depth, with maximum flow velocity increasing from 2.58 to 3.16 mm/s between the 2-year and 100-year return periods. Moving upstream and downstream of Wadi Tamda, we see that the velocity increases in the center and at the outlet due to the topography of the area studied (Fig. 15). The velocity varies between the section's right and left banks, with the river having a higher velocity. In general, flow velocity has a direct impact on erosion and floodwater volume. According to the simulation, built-up areas along the river's right bank Khafoura can be impacted by erosion and floodwater volume, which can reach depths of 3.5m for the 2-year return period and 4.3m for the 100-year return period. Farmland along Wadi Tamda can be submerged due to the topography of the Doucen region, which is a low-lying plain, and this topography is said to be the origin of the name Doucen (Gsell, 1911).

Table 8: Values obtained from hydraulic modeling of Wadi Tamda by HEC-RAS 2D

Return period (years)	Water depth (m)	Max. flow speed (mm/s)
2	3.517	2.586
5	3.914	2.685
10	4.024	2.813
20	4.094	2.951
50	4.146	3.060
100	4.374	3.160

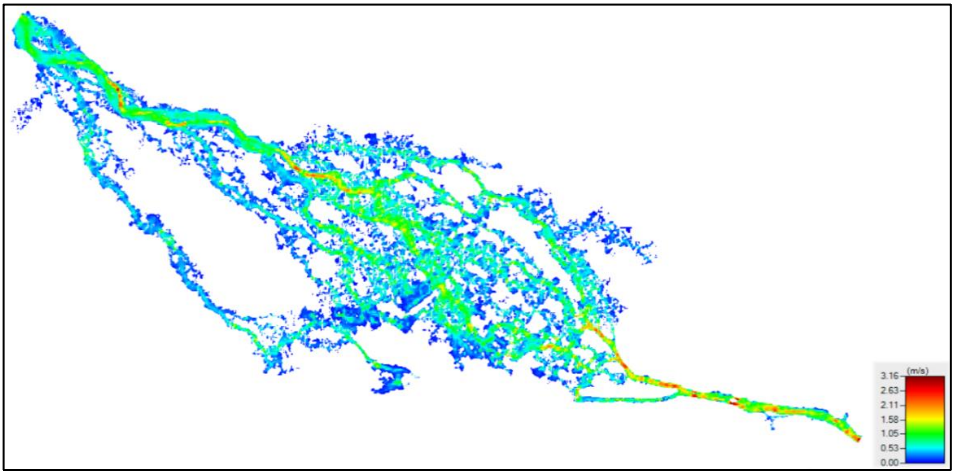

Figure 15: Flood flow velocity along Wadi Tamda for 100-year return period

The Doucen region experienced heavy flooding in September 2009 as a result of nearly a week's worth of rainfall, with over 60 mm falling in 48 hours. This unusually high total for the region contributed to the Wadi Tamda's overflow. This resulted in the following damage: 164 flooded and damaged houses, 9790 palm trees whose harvest was lost, 744 greenhouses destroyed, and 200 hectares of field crops. The increasing frequency of flooding in arid regions can be attributed to the interaction of climate change and urbanization. Climate change, in particular, exacerbates extreme weather conditions such as intense precipitation, increasing the frequency and severity of floods. It exacerbates the situation by forming non-permeable zones that allow surface runoff, reducing soil absorption capacity and increasing the risk of flooding (Suresh and Pekkat, 2023).

Rapid urbanization in arid areas has had a significant impact on existing infrastructure and sewerage networks, increasing social instability and vulnerability to flooding (Eslamian and Eslamian, 2022; Hassan et al., 2022). Population growth in the Doucen region will double by 2050 from 14962 in 2020 to 29598 in 2050, increasing in urban areas. Furthermore, the combination of population growth, urbanization, and climate change is contributing to catastrophic flooding and water supply issues (Bdour, 2022). Studies highlight the impact of population growth on urban flooding, emphasizing the importance of addressing the underlying cause of the expansion of impervious areas (Mazzoleni et al., 2023; Park and Park, 2018). Furthermore, uncertainty about the nature of rainfall patterns in arid zones, combined with poor watershed management and insufficient vegetation cover, significantly increases the severity and danger of flooding, making its occurrence difficult to forecast (Eslamian and Eslamian, 2022). To counteract the rising flood risk in these areas, certain mitigation measures are recommended, such as better planning for optimal urban drainage and stormwater management techniques.

Spatial planning

To reduce the risk of flooding, urban planning must incorporate flood management strategies. Urban flooding is mitigated using infrastructure such as retention basins and drainage channels. To prevent these floods at various critical points, it is proposed to build dikes to store and attenuate the heavy flow (Mehta al., 2024). The Doucen region has long been prone to drought, followed by flash floods, prompting the community to construct a storage dam in the El-Tamda area. The stone barrier's remains indicate that this was a traditional, simple, low-height dam built by locals in a narrow spot to store water from the Muhaysar and Brouth valleys, as well as the tributaries of the Wadi El-Tamda under study, about 1 km from the ancient town. According to the ruins, the dam used a system to control the amount of water that flowed beyond its capacity in order to maintain its strength and stability. Drains were installed on the dam to prevent flooding, and waterways were connected and extended to supply water to many farmlands (Laurent, 1859). The restoration of this small dam or retention basin is critical to reducing flooding severity and enabling proper water resource management while accounting for climate change, agricultural activity, and urban expansion.

CONCLUSION

Natural hazards, such as flooding, encompass a broad spectrum of possible dangers associated with natural phenomena, including climate change. The objective of this study is to evaluate the potential for flooding in the Wadi Tamda basin in Doucen, a desert region in southern Algeria, as a result of factors such as heavy precipitation, population expansion, and the topography of the drainage area. In addition, he emphasizes the significance of hydraulic modeling and risk mapping in formulating flood management strategies and alleviating the consequences of flooding. Desert cities face substantial difficulties from natural hazards, such as flash floods, because of the combination of fast urban growth and climatic conditions. An essential aspect of flood management and safeguarding the well-being of people and infrastructure in the Wadi Tamda watershed in Doucen is the assessment of flood risk. This assessment was carried out using hydrological modeling and the HEC-RAS model. The method was utilized to forecast the amount of water runoff on the surface during floods with recurrence intervals of 2, 5, 10, 20, 50, and 100 years.

The corresponding flow velocities for these floods are 2,586, 2,685, 2,813, 2,951, 3,060, and 3,160 millimetres per second, respectively. The agricultural areas, specific regions in Khafoura, and certain parts of Doucen have been significantly impacted. Urbanization, along with the impacts of climate change, heightens the susceptibility to flooding. This necessitates meticulous urban planning, implementation of effective stormwater management methods, and the establishment of infrastructure like retention basins to alleviate the consequences of urban flooding. Rehabilitating conventional dams or retention basins can have a pivotal impact on flood and water resource management while considering climate change, agricultural activity, and urban expansion. This comprehensive evaluation provides valuable insights for future measures to mitigate the impacts of flooding, prevent loss of life, and minimize material damage.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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