ORIGINAL ARTICLE

Coupling HEC-RAS and HEC-HMS in rainfall–runoff modeling and evaluating floodplain inundation maps in arid environments: case study of Ain Sefra city, Ksour Mountain. SW of Algeria

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Abstract

Ain Sefra watershed is located in the south-west of Algeria that has an area of 1957 km^2. In its downstream part located Ain Sefra city where wadi Ain Sefra (junction of wadi Breidj and Tirkount) takes place. It crosses the completely urbanized areas where it was liable to many inundations causing lots of losses either economic or loss of life, these damages resulted from growth population and the spreading of the city over the natural space of this wadi. In this paper, the methodological approach adopted, focused on the hydrologic modeling through the Hydrologic Engineering Center's Hydrologic Modeling System and the hydraulic modeling under the Hydrologic Engineering Center's River Analysis System with combination of Watershed Modeling System model and Geographic Information System. The aim of this study is to analyze the inundation behavior of Ain Sefra city during extreme flood events by considering concrete retaining walls existence built by local authorities and without it. In this case, three types of simulation are performed with the return periods of 10, 100, and 1000 years. The hydraulic modeling revealed that the existence of retaining walls resulted in decrease of flood zone area, and so much less lands are endangered by floods, so that damages of flood at the study area decrease clearly, but they still been insufficient for all return periods. The simulations also highlighted that the region most affected by the flood is the downtown area. Finally, a protection concept is proposed to ensure a better passage of floods in Ain Sefra city, to reduce the risk and to protect the city against the floods.

Keywords Ain Sefra · Hydrological modeling · Hydraulic modeling · Floods · HEC-HMS · HEC-RAS

Introduction

More people are affected by extreme weather events, especially floods and drought, than by any other type of natural hazard. Flood is one of the most frequently occurring and higher impact natural disasters, that caused losing of lives and properties, and it can be the highest killer weather phenomena. Floods can occur in rivers, reservoirs, and coastal areas with serious damages, when flow exceeds the capacity of the river channel. How to estimate and mitigate the risk of inundation is a crucial question nowadays (Zhang et al. 2014). According to the UN Office for disaster risk reduction, the Centre for Research on the Epidemiology of Disasters: during the last 20 years, flooding has been the most common natural disaster by far, accounting for 43% of all recorded events natural disasters that occurred around the world between 1995 and 2015 which affected a further 2.3 billion people (Guha-Sapir et al. 2016). Global floods and extreme rainfall events have surged by more than 50% this decade, and they are now occurring at a rate four times higher than in 1980 (EASAC 2013), and the number of floods per year rose to an average of 171 in the period 2005–2014, from an annual average of 127 in the previous decade (Guha-Sapir et al. 2016).

The floods represent the most widespread catastrophes in the Mediterranean (Ballais et al. 2005). According to the Plan Bleu which is acting as a Mediterranean Observatory on Environment and Sustainable Development, 249 destroying floods touched the Mediterranean circumference in these

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20 last years (1996–2016). They affected 7861802 people, causing 3474 dead and economic losses which would rise with more than 25 billion euros (EM-DAT 2016). The risings and the floods in the Mediterranean often originate to the torrential rains. The highest flood frequency corresponds to northern Mediterranean countries (Spain and Italy). However, they are less frequent in southern Mediterranean countries (northern Africa), but are usually catastrophic with a very high number of casualties (Llasat et al. 2010). Algeria is one of the Mediterranean countries vulnerable to flooding risks linked to climatic hazards. Where, they have marked as one of the most frequent natural disasters and the most destructive. According to Algerian Civil Defense Directory, floods killed more than 1000 people in Algeria in the last 20 years. While the flood of 10 November 2001 at Bab El Oued district of Algiers is the deadliest with 781 deaths, 115 missing, and 3721 destroyed houses (Menad et al. 2012). In addition, there are more than 700 sites at risk of flooding in Algeria, of which 100 at high risk systematically involving a priority intervention, according to the Ministry of Water Resources. The flood damages will be increased over the years due to population growth and socio-economic development, and the climate change due to the global warming effect. Therefore, it is necessary to define a methodology to predict the flash floods in this region, to protect the city against inundations. The widely used approach to determine flash floods occurrence and the relationships between rainfall and runoff data is the flood inundation modeling (Derdour et al. 2017).

Flood inundation modeling requires distributed model predictions to inform major decisions relating to planning and insurance (Bates 2004). In the recent years, flood hazard assessment has considerably improved especially due to the use of geographic information systems (GIS) in integration with hydrological and hydraulic modeling. The GIS environment has the ability to extract the hydrological variables needed from a good-quality digital elevation models (DEM), such as catchments shapes, flow directions, slopes, path lengths, and watershed delineation (Jenson and Domingue 1988; Wilson and Gallant 2000). Assessments of flood affected areas resulting from extreme precipitation and changing land use can be helpful for better understanding the flood events (Dawadi and Ahmad 2012; Mosquera-Machado and Ahmad 2007; Ahmad and Simonovic 2006). Efforts have also been made to integrate some hydrological models with the GIS environment. Most of these models are physically based distributed models, e.g., HEC-HMS, HEC-RAS, and WMS. This integration allows assessment and prediction of the impact of watershed management practices (Zhang et al. 2008; Wheater et al. 1999; Verma et al. 2010; Arnold et al. 1998).

Some noteworthy examples over the world are as follows. Dang Thanh and Florimond (2017) combined the Hydrological and Hydraulic Model for Flood Prediction in Vietnam. Gül et al. (2010) combined the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) to examine the potential serviceability of a planned dam in the Bostanli basin in Turkey. Bonnifait et al. (2009) used TOPMODEL (TOPography based hydrological MODEL) with a hydraulic model for reconstructing a catastrophic flood event in the Gard region, France. Thakur et al. (2017) coupled HEC-RAS and HEC-HMS to evaluate floodplain inundation map in Illinois State in USA. Berni et al. (2009) used hydrologic and hydraulic modeling for reliable flood risk mitigation activities in the Upper Medium Tiber River basin in Italy. Hashemyan et al. (2015) combined HEC-HMS and HEC-RAS models in GIS to simulate flood in Khoshke Rudan river in Fars province, Iran. Knebl et al. (2005) used NEXRAD rainfall, GIS, and HEC-HMS/RAS in San Antonio River Basin in USA.

Many studies have been conducted also in Algeria to modulate rainfall–runoff relations and to calculate the catchments area and the flash floods discharges for different purposes like runoff harvesting or creating flash floods hazards maps. As example: Derdous et al. (2015) used GIS-based approach for the prediction of the dam break flood hazard in Zardezas reservoir in Skikda. Derdour et al. (2018a) modeled rainfall–runoff relations using HEC-HMS in a semi-arid region in Ain Sefra watershed. Skhakhfa and Ouerdachi (2016) used HEC-HMS model for the hydrological modeling of wadi Ressoul watershed. Astite et al. (2015) cartographed flood hazard by overflowing rivers using hydraulic modeling and geographic information system in Oued El Harrach. Yamani et al. (2016) combined HEC-HMS and HEC-RAS to mapping of vulnerability of flooded area in arid region in Ghardaia city. Atallah et al. (2018) simulated the extreme flood events in Sidi Bel Abbes city. Laouacheria and Mansouri (2015) used HEC-HMS model by employing frequency storm to simulate the runoff in a small urban catchment in the North-East of Algeria. Bekhira et al. (2018) used GR model to predict of floods in the Wadi Bechar watershed.

This paper focuses on the simulation of the occurrence of floods in Ain Sefra city which is situated in the western part of Ksour Mountains, this area subjected to severe flash floods since the creation of the modern city in 1882 as previous records in 1904, 1990, 2000, and 2007, and the most recent flood was in 2014, by constructing hydrologic and hydraulic models using HEC-HMS, HEC-RAS, WMS, and GIS, and it is based on four models, a flood hazard map will be developed to help the decision-makers to identify the areas within the city with high risk of flooding and to test the impact of developments carried out, which can help them in adopting appropriate plans to manage the risk and to take the necessary measures to reduce the effects of floods to eliminate the life losses and to limit the material damages.

Study area

The region of Ain Sefra is situated in the Ksour mounts, at the south-west of Algeria. It is located between longitudes (1°3′54″ and 0°26′05″W) and latitudes (32°27′5.76″ and 33°2′11.5″N) (Fig. 1). The Ksour mounts is a rather high mountainous region formed by extended chain mounts towards the South-west and North-east. According to the Directorate of programming and budget monitoring of the wilaya of Naama, the total population of Ain Sefra city is around 73,211 inhabitants, with a density of 72.85 (Hab/km²) (DPSB 2018).

Ain Sefra watershed has an area of 1957 km²; it is as a landlocked basin surrounded by Ksour Mountains. With 67 km of length, the longest flow path runs southwestward from its origin in the north side of Morghad Mountain, and receives wadi Sfissifa (wadi: local term of channel that is dry except in the rainy season); together, they form wadi of Breidj, and they pursue the same direction to meet wadi Tirkount. These two wadis (Breidj and Tirkount) cross through the city of Ain Sefra, and meet in the center of the urban area to form wadi Ain Sefra, that is run to the south at downstream of the study area while receiving other wadis as Tiout and Sam, to become at the end wadis Namous that is lost in the great western Erg in the Algerian Sahara at 370 km from its origin. The watershed of Ain Sefra is moderately elongated and characterized by a fairly widespread network, steep slopes, and relatively impermeable terrains with variety lithology, providing a favorable environment for the development of flashfloods (Derdour et al. 2017). The occupation of watershed ground
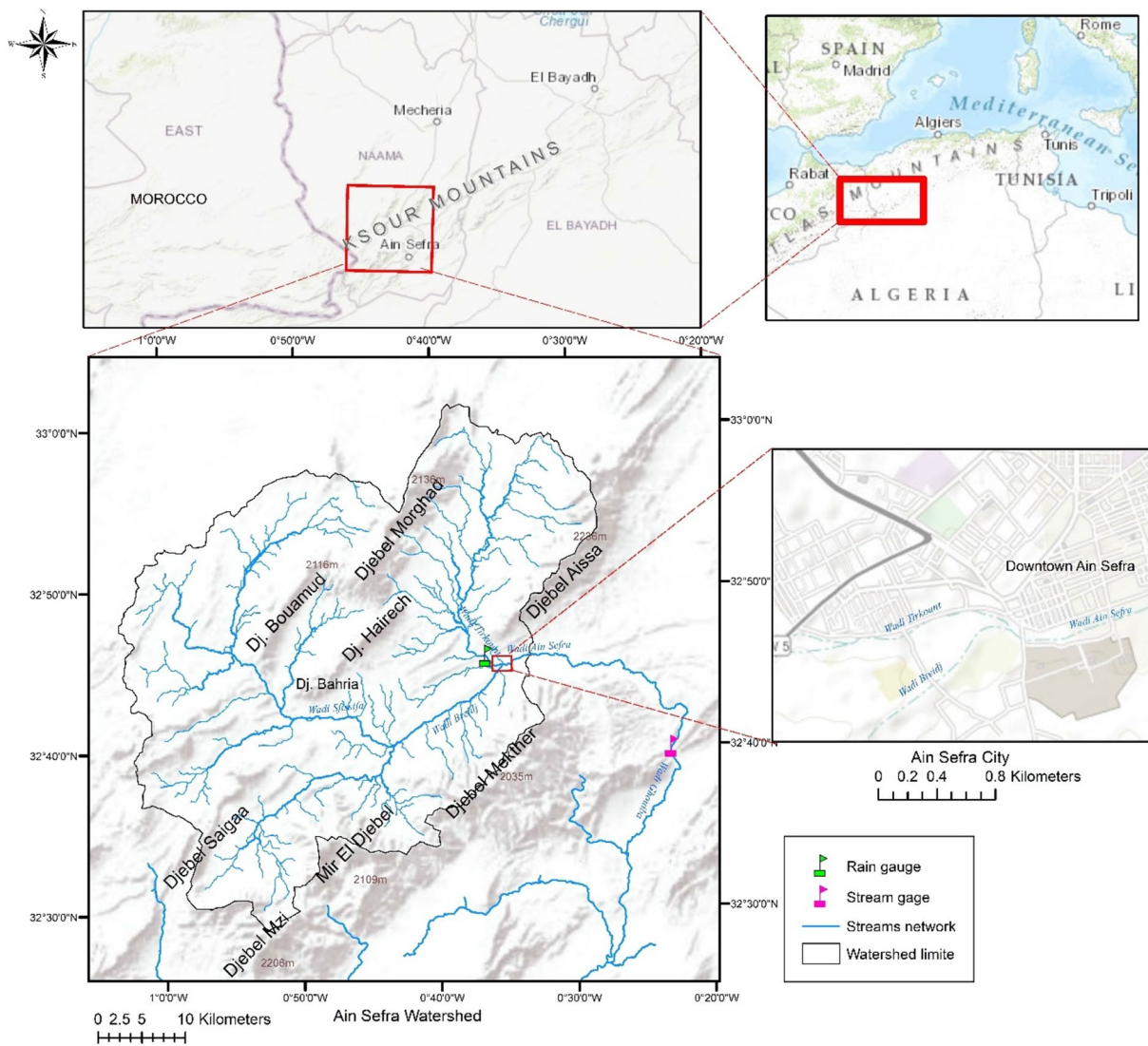

Fig. 1 Location map of the study area

shows that the main dominant lands in the basin are the grasslands (56.2%), the forest land (29.2%), bare areas (6.6%), and outcrop lands (4.4%). The rest are in minor proportion: agricultural lands (1.8%), sand lands (1.6%), and urban areas (0.3%) (Derdour et al. 2017). The dominant geologic formation is the sandstone rocks (Jurassic and Cretaceous), but they are usually clayey interspersed by marl or compact quartz, their permeabilities are generally very low, except for the Albian sandstone which constitute the most important groundwater aquifer in the region which is characterized by confined to semi confined conditions (Rahmani et al. 2017). Ain Sefra watershed is characterized by relatively steep slope upstream, the slope decreases downstream from the confluence of wadi Sfissifa with wadi Breïdj. The ground elevation varies from 1058 to 2213 m above the mean sea level. The mean elevation is 1334 m and the mean basin slope is 5.8 m/km. There are three types of slopes: a relatively low slope between (0 and 6%) at low altitudes (1058–1400 m), occupying 79% of the total area of the watershed; a moderately steep slope between (6 and 25%) at moderate altitudes (1400–1600 m), where area occupied is about 12%; more steep slopes (over 25%) at altitudes (1600–2213 m) occupying 8% of the total area of the basin, these slopes give the wadi a violent and torrential type.

Ain Sefra watershed is sub divided into two major sub-basins (Breidj and Tirkount).

Table 1 summarizes the principal characteristics of each sub-basin. Ain Sefra city presents the outlet of the watershed; the majority of the activities are concentrated on the level of the wadis of Breidj and Tirkount which generates significant damage in case of rising.

Topographic data describe the geometry of the simulated watershed system. The hydrological modeling does not require a very fine spatial resolution; that is why, we use digital elevation models (DEMs) with 30×30 m resolution sourced from Shuttle Radar Topographic Mission (SRTM). On the other hand, the hydraulic modeling requires a finer spatial scale. Thus, the accuracy of the calculation of water-surface elevation closely on the accuracy of the topographic data, and given the absence of topographic maps of a high spatial resolution of Ain Sefra city, we carried out a land survey along the wadis (Breidj, Tirkount and Ain Sefra) using a Topcon-type GPS land surveying (Fig. 2). The Topcon GPS station is able to perform measurements with extreme accuracy, "horizontal resolution of 0.004 m, and altimeter accuracy of 0.01 m".

Table 1 Morphometric parameters of sub-basins

Sub-catchment	Area (km²)	Perimeter (km)	Compactness index (KC)	Channel slope %	Stream length (km)
Tirkount	579.55	143.34	1.66	9.56	44.51
Breidj	1373.44	269.2	2.03	9.31	67

Fig. 2 Measures at the stream centerline (**a**); measures above the retaining walls (**b**)

(a)   (b)

Climate conditions

Meteorological data for the study area are obtained from a weather station installed at Ain Sefra city. The station WMO code is 605600 and its coordinates are 32°45′N, and 0°35′39″W. The weather station is managed by the ONM (National office of Meteorology). The series of data available from 1980 to 2014 provided by this station shows that the climate of Ain Sefra is characterized by high temporal and spatial irregularity. The annual average rainfall is about 185 mm, where the maximum annual rainfall is 439.8 mm, registered in 2008 (Fig. 3). The average monthly rainfall is of the order of 30.64 mm for the wettest month (October), and it is 3.92 mm for the driest month (July). The rainfall is very irregular and the rain storms are rare but intense which initiate and control the occurrence of flash flood event. The analysis of the series indicates that the climate of the area of Ain Sefra is typically semi-arid to arid. It is divided into two main seasons: one moderate season with often rain intensities (from October to March) and another hot and dry season (from April to September) (Derdour et al. 2018a).

Between 1980 and 2014, the annual temperatures at the meteorological weather station of Ain Sefra city vary between 15.5° C and 20.5° C, where the average annual temperature is around 17.5° C.

Overview of the flooding of the region of Ain Sefra

Ain Sefra is one of the Algerian cities, which is affected by risings which generally generate floods due to the overflows of the wadi crossing the city. Throughout history, Ain Sefra city witnessed flooding during several years: 1904, 1949, 1977, 1990, 2000, 2007, and 2014. Floods in the Ain Sefra wate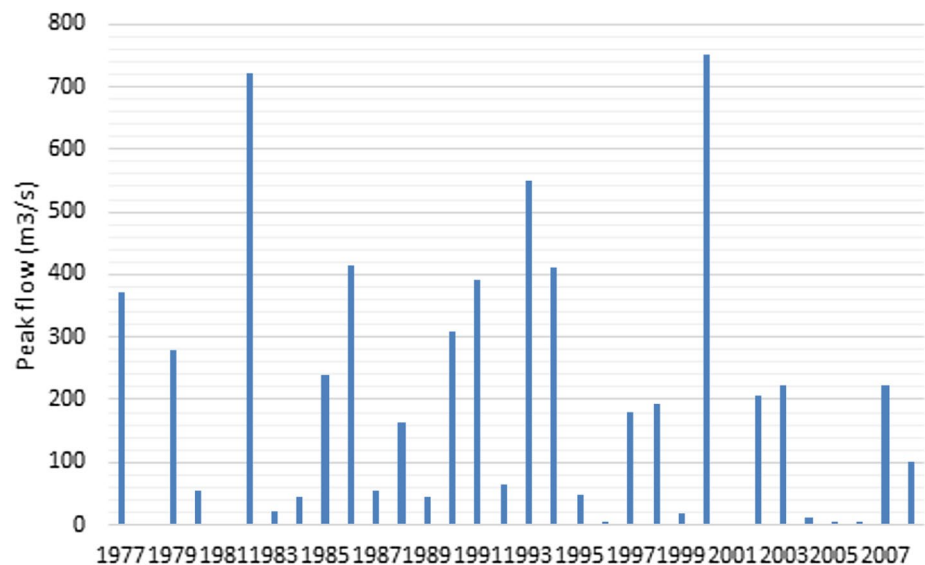rshed are exclusively result from heavy rains. As an example: the 1990 flood which occurred on 5th May was catastrophic where Ain Sefra city received 113.4 mm of rainfall, while the month average rainfall is only 20.5 mm. Table 2 summarizes the most significant floods.

The analysis of peak flows measured over a period of 32 years (from 1977 to 2008) at the stream gaging station of Ain Hadjadj (20 km downstream from Ain Sefra) is based on the data collected from the National Hydric Resources Agency (ANRH). (Figure 3) noting that no data available after 2008 in this station.

The morphology of the watershed helps to amplify the peak flows observed at the outlets which vary from a few m^3/s to 751 m^3/s where the maximum is registered in October 24th, 2000. From 16 registered events ($Q_{max} > 100$ m^3/s), October is reported as a high-risk month with 11 floods that is represented 69% of the floods in the series. Also, the region has experienced three peak flow surges exceeding 500 m^3/s.

Floods in Ain Sefra are highly variable and irregular, short, and stormy, with very high peak flows if compared to the average modules, and they are characterized by a very fast rise, leading severe damages in Ain Sefra city, and a slow decline followed by a prolonged dry period (from April to September). Autumn is reported as risky season. However, the flow in dry periods demonstrates a groundwater potential, which is produced by the Atlas relief that shows a fairly strong hydrological relationship between surface water and groundwater. The downtown of Ain Sefra represents the most exposed zone with the effects of the floods whose consequences are catastrophic. The known zone is located at the junction of wadi Breidj and Tirkount.

Fig. 3 Distribution of peak flow from 1977 to 2008

Table 2 The most significant floods in Ain Sefra city

Date	Description of the disaster
October 10, 1904	Significant casualties, about 26 dead including the famous writer Isabelle Ebehardt. The French general Girault denounced the stupidity of the architects, engineers and officers who threw the first foundations of the modern city. For him, the disaster was not only due to fatality (Girault 1905)
March 17, 1941	Exceptional floods. Extensive material damage was registered at the city of Ain Sefra (Dubief 1955)
May 20, 1949	Major flood, it causes important damage to several places in the city of Ain Sefra (Dubief 1955)
October 26, 1977	With a peak flow estimated at 373 m^3/s, it caused significant material damage in the popular neighborhoods of the city of Ain Sefra. The flood lasted nearly 35 h; the peak flow was reached after 8 h, while the recession took 27 h to return to the initial flow (three times the rise time)
May 05, 1990	Huge flooding. Very important material damage; water levels reached almost 2 m in the neighborhoods of the downtown of Ain Sefra. The gauging station registered a peak flow of 392.72 m^3/s and a volume of 27.71 million cubic meters during the flood period
October 22, 2000	A family of five people died; several inhabitants were forced to leave the places giving place to the furies of the waters. The streets and alleys were completely paralyzed, important damage. The rise of floods lasted 6 h and the recession took 29 h to return to the initial flow (five times the rise time). Flow rates reached a record with a peak of 750.8 m^3/s
November 14, 2004	The torrential rains that hit the area caused extensive material damage in the populous areas of the city of Ain Sefra. The streets and alleys were completely paralyzed, significant material damage. With a peak of 206 m^3/s
October 19, 2007	Major damage in downtown Ain Sefra. Many bridges at the watershed level have been damaged, with a peak of 221.7 m^3/s
May 31, 2011	Considerable damage in downtown Ain Sefra
October 1, 2014	An 11-year-old child swept away by the floods. Extensive damage

Methodology

The physically based conceptual approach with available data that provides more insight into the physical nature of the watershed (surface and topography) and meteorological (rainfall and runoff) has been adopted. In our study, flood inundation modeling was conducted using HEC-HMS after passing with WMS (Watershed Modeling System) model, to construct an HEC-RAS flow model. The advantage of using WMS is its interchangeability with GIS, HEC-HMS, and HEC-RAS. WMS can perform operations such as automated basin delineation, geometric parameter calculations, GIS overlay computations, cross-section extraction from terrain data, floodplain delineation, mapping, and storm drain analysis (Myronidis et al. 2009).

The first step in the development of a floodplain analysis is to collect highly detailed information grouped into three categories: hydrologic, hydraulic, and topographic.

Hydrologic and hydraulic data consist of rainfall, discharge hydrographs, and stage historical records. They are obtained from the National Hydric Resources Agency (ANRH) and the National Office of Meteorology (ONM) at Ain Sefra city.

The proposed method consists of ten steps after data collection:

- The first step is to build the intensity curve–duration–frequency (IDF), and then estimates the peak discharges (Q_{max}) using a statistical method for different average recurrence interval.

- The second step, defining basin delineation, stream network, topography, and geometric characteristics by DEM processing, using ARC GIS and WMS model (Myronidis et al. 2016).

- The third step, modeling rainfall/runoff relation, using HEC-HMS model. Which includes four steps (1) sub-basin delineation; (2) hydrologic parameter estimation; (3) model set-up by building basin model, meteorological model, and control specifications; (4) calibration and validation (Scharffenberg and Fleming 2010).

- The fourth step, creating the triangulated irregular network (TIN) of the city of Ain Sefra with high resolution (altimeter accuracy of 0.01 m) and rich in topographic details established from topographic land surveys. That represents the topography of the study area.

- The fifth step, extracting cross-sections from the TIN in WMS,

- The sixth step, importing the hydrologic modeling results to be used as input data in hydraulic model HEC-RAS.

- The seventh step, creating a conceptual model such as the river reaches, the stream centerline, the main channel banks, the cross-section lines, and the material zones which are called channel geometry.

- The eighth step, defining the network schematic on HEC-RAS using Manning's roughness coefficient (n) for every land-use type.

- The ninth step, applying a steady gradually varied flow analysis which consists of peak discharge information, boundary conditions, and flow regime to compute water-surface elevation along the channel geometry of wadi Breidj, Tirkount, and Ain Sefra.

- The final step, floodplain delineation is conducted to obtain the flood inundation area involving a flood depth and a flood extent for the wadis Breidj and Tirkount and their junction wadi Ain Sefra using WMS and HEC-RAS. In this case, three types of simulation will be carried out: (1) determining the flood zones with the return periods of 10, 100, and 1000 years without taking in consideration hydraulic developments which are done in the city of Ain Sefra, by the water resources directorate; (2) determining the flood zones with the same previous return periods but with taking into account hydraulic developments; (3) the third simulation taking into account the solutions that we propose to reduce flood damage in the area.

The methodology of the study is illustrated in Fig. 4.

Description of the software used

Runoff is modeled using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), version 4. HEC-HMS is a physically based, semi-distributed hydrologic model developed by the US Army Corps of Engineers (Scharffenberg and Fleming 2010). It is designed to simulate the complete hydrologic processes of dendritic watershed systems. The software includes many traditional hydrologic analysis procedures such as event infiltration, unit hydrographs, and hydrologic routing. HEC-HMS also includes procedures necessary for continuous simulation including evapo-transpiration, snowmelt, and soil moisture accounting. Advanced capabilities are also provided for gridded runoff simulation using the linear quasi-distributed runoff transform (ModClark). Supplemental analysis tools are provided for model optimization, forecasting streamflow, depth-area reduction,

Fig. 4 Methodology adopted for the study
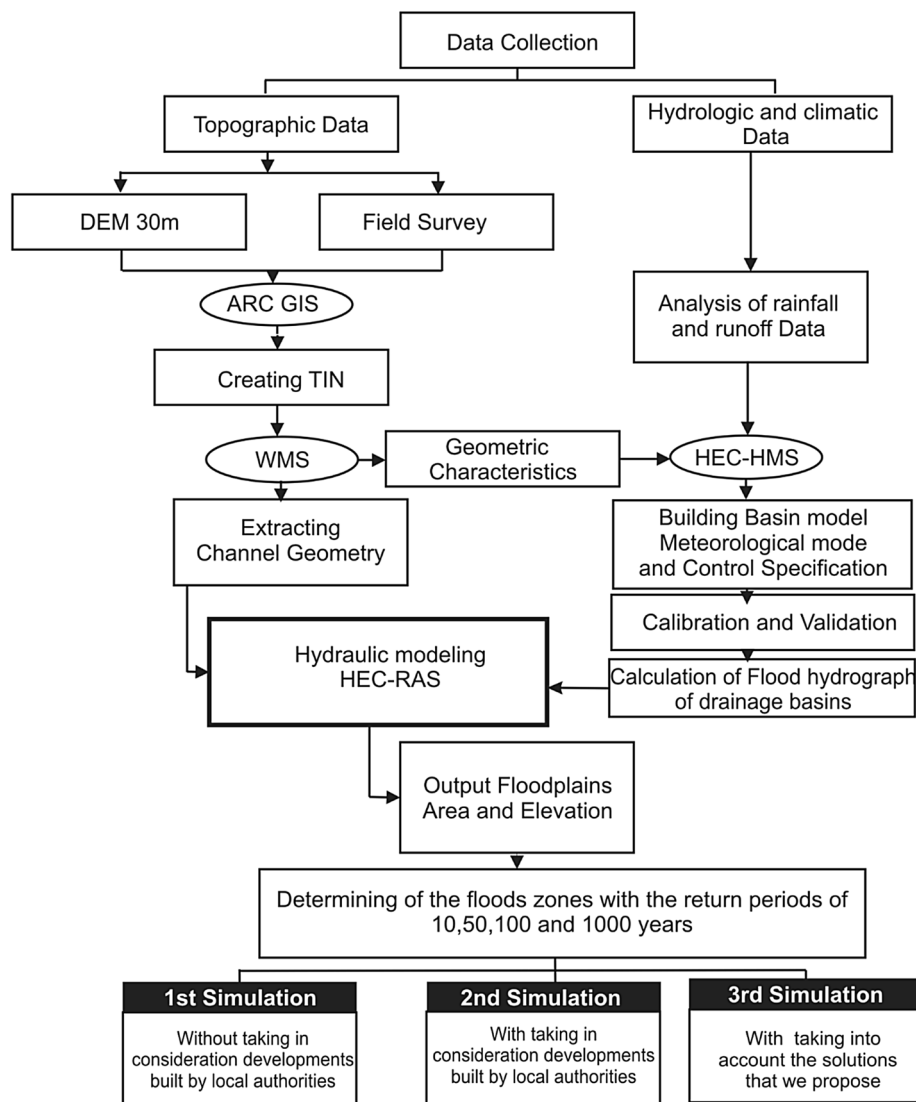
assessing model uncertainty, erosion and sediment transport, and water quality. HEC-HMS is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and system operation (Scharffenberg and Fleming 2016). The program has an extensive array of capabilities for conducting hydrologic simulation. Many of the most common methods in hydrologic engineering are included in such a way that they are easy to use. The program does the difficult work and leaves the user free to concentrate on how best to represent the watershed environment (Scharffenberg and Fleming 2016).

Flood propagation and inundation levels in the floodplain are simulated with the Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) developed by the Hydrologic Engineering Center of the US Army Corps of Engineers (USACE). HEC-RAS calculates one-dimensional steady and 1D and 2D unsteady flow. HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics, and reporting facilities. The HEC-RAS system contains four hydraulic analysis components for: (1) steady-flow water-surface profile computations; (2) one and two-dimensional unsteady-flow simulations; (3) movable boundary sediment transport computations; and (4) water temperature and constituent transport modeling (Brunne 2016).

The hydraulic model requires as input and the output hydrographs from HMS; its parameters are representative cross-sections for each sub-basin, including left and right bank locations, roughness coefficients (Manning's n), and contraction and expansion coefficients. Roughness coefficients, which represent a surface's resistance to flow and are integral parameters for calculating water depth, were estimated by combining land-use data with tables of Manning's n values. The version 5.0 of HEC-RAS supports steady- and unsteady-flow water-surface profile calculations, sediment transport computations, and water-quality analyses. The software also contains tools for performing inundation mapping directly inside the software. A full description of the model and its computational schemes is given by Brunne (2016).

Results and discussion

During the land survey of Ain Sefra city along the minor and major riverbeds, 1925 points were registered on a linear of 3.3 km to obtain the triangulated irregular network (TIN) of the city with high resolution (Fig. 5). This TIN resolution is very favorable to be applied for a floodplain area to assess flood hazards.

A total of 55 cross-sections were taken over the reaches modeled as shown in Fig. 6. The great number of cross-sections was chosen for more details of flood maps. Roughness coefficients used in the study area were 0.04 for cropland, 0.08 for urbanized area, 0.035 for rivers, and 0.01 for concrete in the retaining walls zones according to Henderson (1966).

Analysis of rainfall and runoff data

The records from Ain Sefra rainfall station were obtained and analyzed to establish the intensity–duration–frequency (IDF) curves based on extreme value, to evaluate the watershed reaction to a given rainfall event. In this study, we assumed that the entire watershed would receive the same amount of rainfall. The rainfall IDF results adopted for the area for various storm durations and average recurrence interval (ARI) are shown in Fig. 7.

After having tested several statistical methods employed in flood frequency analysis (FFA) (exponential, GUV, gamma, Gumbel, normal, and log-normal), peak discharges of wadi Ain Sefra during 32 years fit well with the Gumbel approach (Derdour et al. 2018b). This statistical method employed allows us to estimate the peak discharges (Q_{max}) for different average recurrence interval (Table 3).

Hydrologic modeling results

The hydrologic modeling is based in a previous study done by Derdour et al. (2018a); which simulate runoff in Ain Sefra watershed through the employing of the Hydrologic Engineering Center—Hydrologic Modeling System (HEC-HMS) where the frequency storm is used for the meteorological model, the Soil Conservation Service curve number (SCS-CN) is selected to calculate the loss rate and Soil Conservation Service unit hydrograph method has been applied to simulate the runoff rate.

The calibrated HEC-HMS model was used to calculate direct peak discharges for wadi Ain Sefra and for the two ungauged sub-catchments (Breidj and Tirkount) for various average recurrence intervals (10, 100 and 1000 years). The Nash–Sutcliffe efficiency coefficient was 0.95, which indicates that the hydrological modeling results are satisfactory
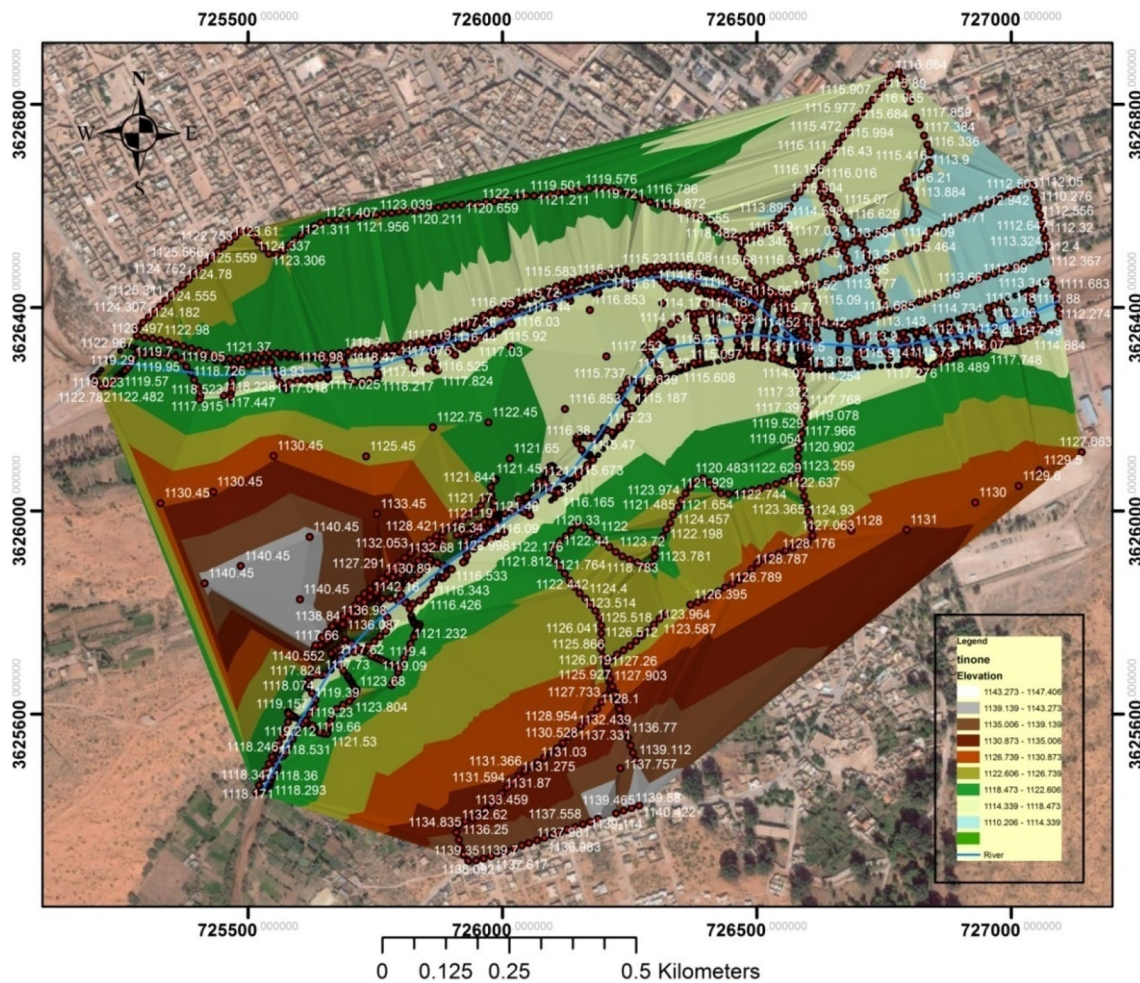
Fig. 5 TIN of the study area

and accepted for simulation of rainfall–runoff (Derdour et al. 2018a). Table 4 shows the peak discharge flowing from each catchment.

Hydraulic modeling results

For hydrodynamic modeling, the model HEC-RAS was considered. This model solves the problems of the flows on free surface permanent or non-permanent. It solves the equation of unidimensional energy, the losses being evaluated by the formula of friction at the bottom of Manning–Strickler and by formulas of contraction/expansion of the flow. Hydraulic modeling is used to produce flood hazard maps in Ain Sefra city. The peak discharge data for each catchment calculated with HEC-HMS are used as an input to the HEC-RAS to model the water depths and along the flood path. The result was imported and readied by WMS for all return periods. In HEC-RAS, the flood path is defined through 55 cross-sections extracted from the TIN of the study area. The initial model has on average

1 profile every 60 m. To have an even finer space step, we created cross profiles by interpolation of the extracted profiles, and we added a profile as soon as the distance between two profiles exceeded 20 m, so the flood path is defined through 165 cross-sections.

The cross-sections width is 100 m for wadi Breidj and Tirkount, and 150 m for wadi Ain Sefra which represent the downtown zone. Roughness coefficients (Manning's) used in the study area were 0.04 for cropland, 0.08 for urbanized area, 0.035 for rivers, and 0.01 for concrete in the retaining walls zones (Henderson 1966). The flow regime in HEC-RAS is set to be mixed. The upstream boundary condition is set as a critical depth, while the downstream end is set as a normal depth. After fulfilling all the input data and boundary conditions in HEC-RAS, the simulation is done as a steady-state analysis.

The flood hazard maps were prepared by considering of concrete retaining wall existence and without it. In this case, three types of simulation are performed:
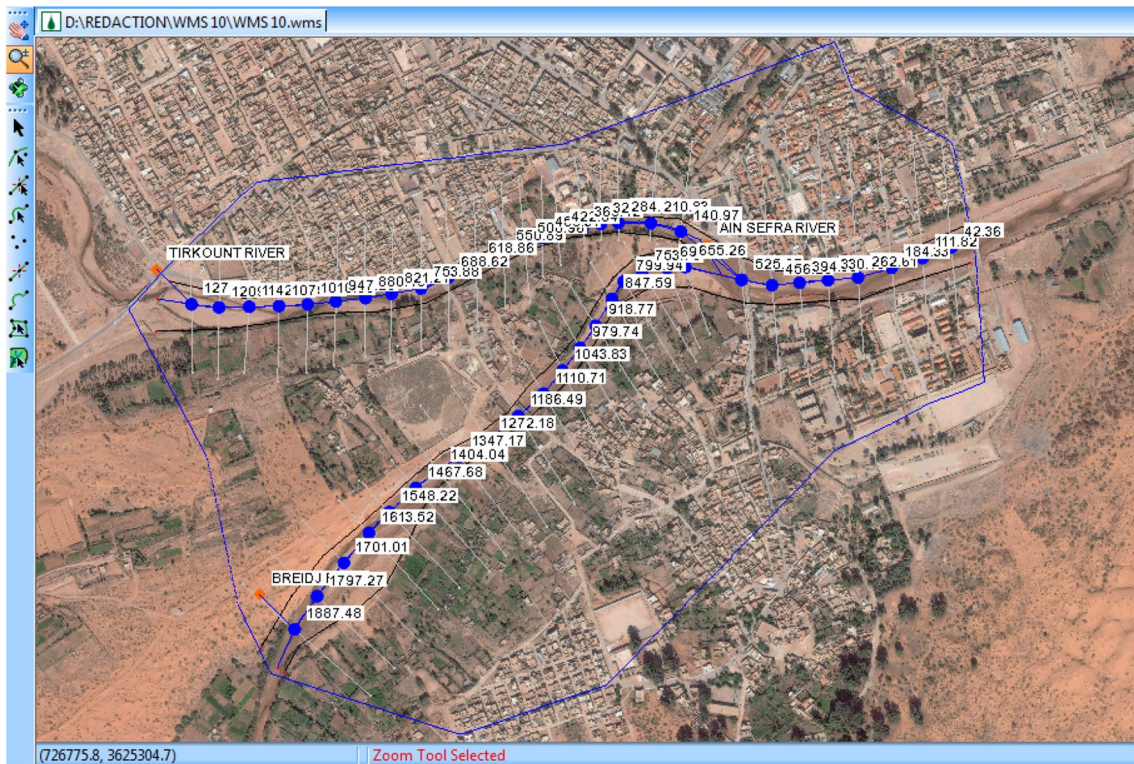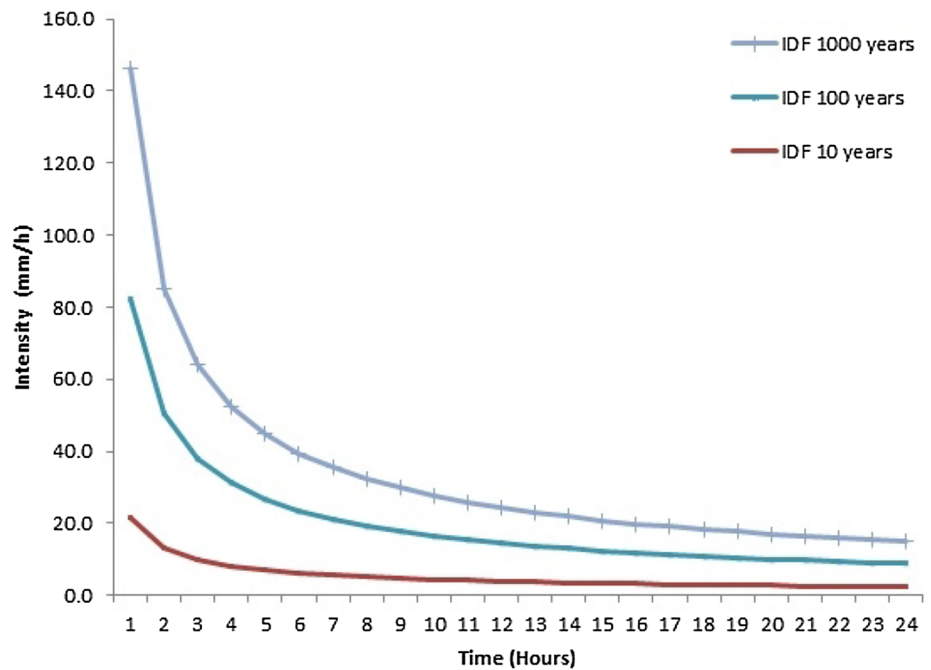
Fig. 6 Extracting cross-sections of the study area

Fig. 7 Curves IDF "intensity–duration–frequency"

First simulation

The purpose of the first simulation is to determining the flood hazard map with the return periods of 10, 100, and 1000 years without taking into consideration retaining walls built by local authorities in their flood-fight effort. The peak discharge calculated by HEC-HMS was inputted into and generated by HEC-RAS; the result was imported and readied

Table 3 Peak discharges with Gumbel approach

Flow (m³/s) when average recurrence interval (years)		
10	100	1000
463	845	1120

by WMS for all return periods. The WMS interpolate the results of water-surface elevation data and delineate the flood inundation, as shown in Figs. 8, 9, and 10 for 10-year, 100-year, and 1000-year flood. This simulation revealed that the region most affected by the flood is the downtown area. This region represents the junction of wadis Breidj and Tirkount; it is marked by low altitudes. The water depth in this area exceeds 4.44 m downstream for a 10-year flood, and the

width of the flooded areas reached during the 100-year flood and 1000-year flood was 501 m and the 600 m, respectively.

Second simulation

After the flood of 19/10/2007, and to stabilize the banks against erosion and to prevent overflowing, local authorities of wilaya of Naama, built concrete retaining walls in several vulnerable areas in Ain Sefra city. The realized linear is about 1.9 km and total cost of the operation is 3.2 million Euros (Figs. 11, 12). The aim of the second simulation is to testing the performance of concrete retaining walls already built by local authorities in their flood-fight effort.

Depictions of the 10 years, 100 years, and 1000 years of flood hazard maps were simulated to provide a

Table 4 Peak discharge (m³/s) for the sub-catchment

Average recurrence interval years	Hypothetical storm (mm)	Simulated peak discharges (HEC-HMS) (m³/s)		
		Wadi Breidj	Wadi Tirkount	Wadi Ain Sefra
10	56.9	301.1	227.0	425.8
100	106	641.9	473.0	904.3
1000	166	943.5	687.3	1328.3
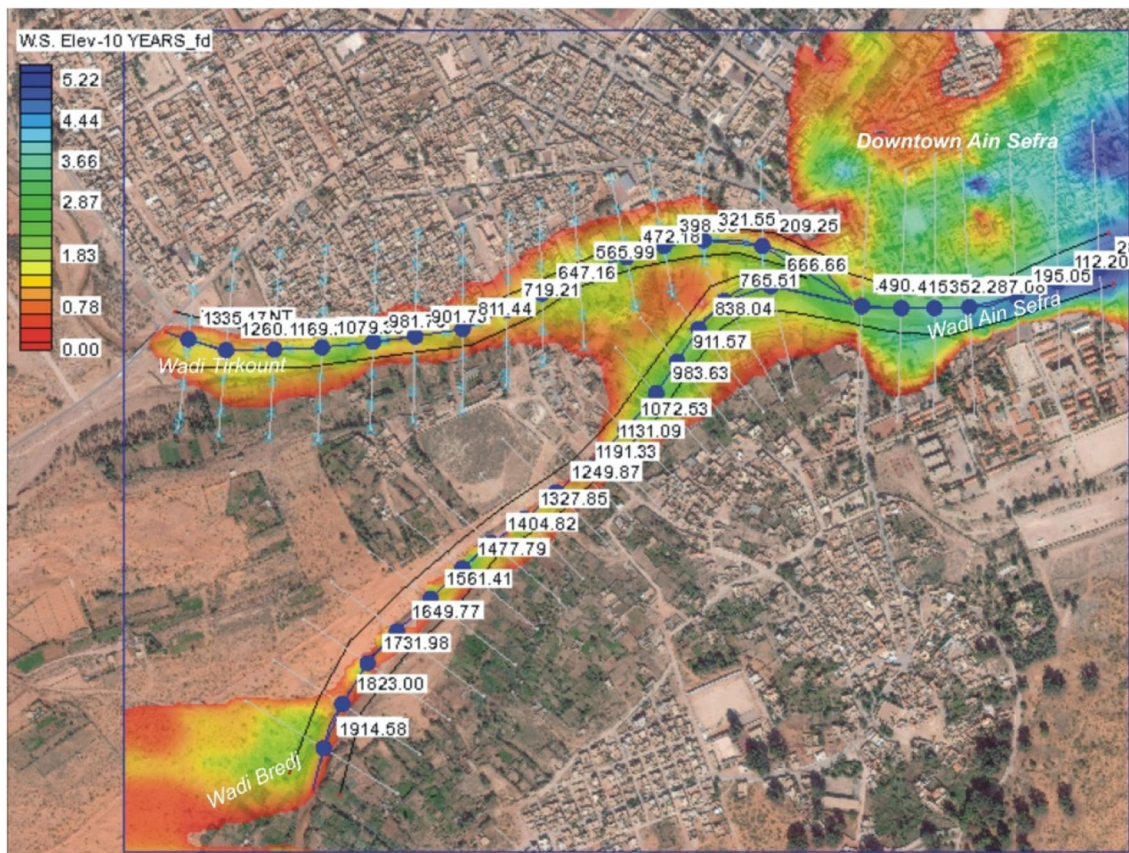
Fig. 8 Flood inundation map in Ain Sefra city (return period 10 years)
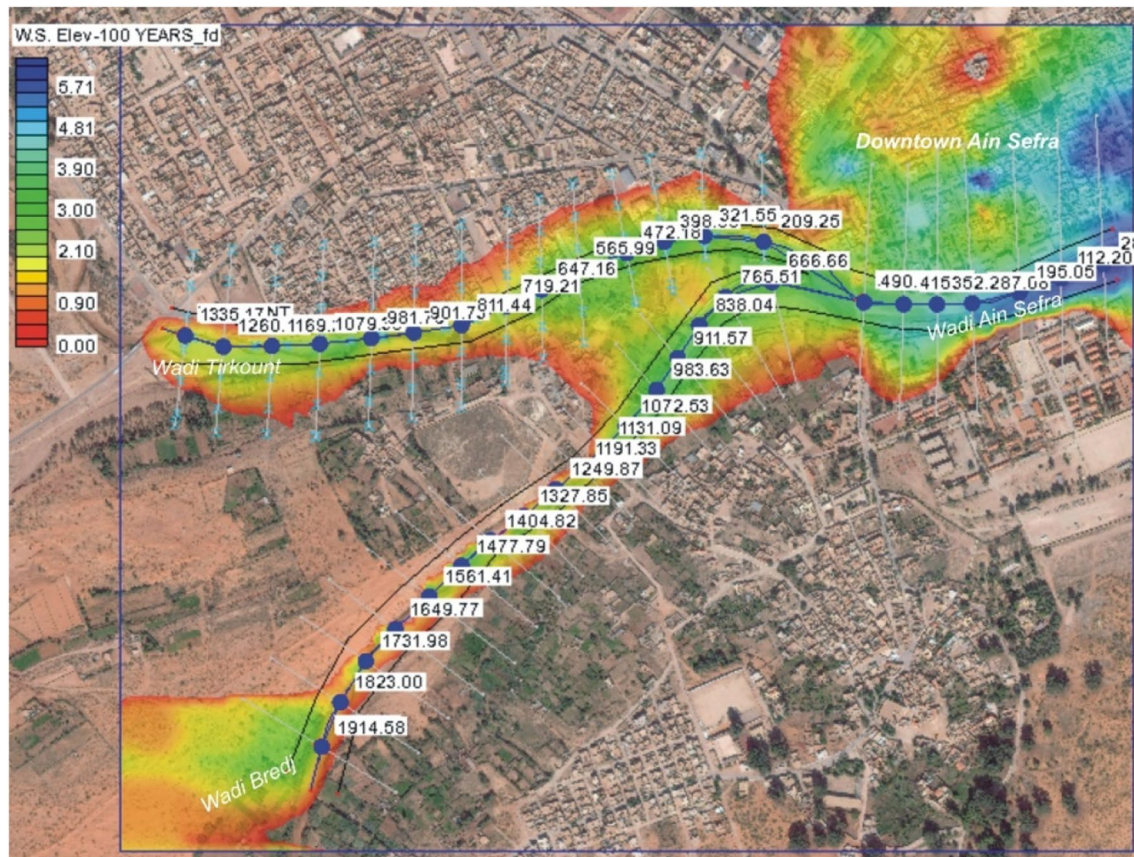
Fig. 9 Flood inundation map in Ain Sefra city (return period 100 years)

representation of the floodplain boundaries that are commonly used for flood insurance purposes. The model HEC-RAS shows its capacity as representation of extended of the flood and to specialize well the elements exposed at this risk in three-dimensional view (3D) and by consequence to lead to a tool of decision-making integrated well. Figure 13 demonstrates the flood inundation map of the study area for the 10-year and 100-year flood. In these sections, we remark that the retaining walls are generally adequate for 10-year floods, where wadi Ain Sefra has no overflow. However, there are some overflows for the 100-year floods. While seen in Fig. 14, the protections done are still insufficient for 1000-year flood for the three wadis (Breidj, Tirkount and Ain Sefra). These simulations revealed that the existence of retaining walls resulted in decrease of the flood zone area, and so much less lands are endangered by floods, so that environmental effects and damages of flood at the study area decrease clearly.

Third simulation

The aim of the third simulation is to test the solutions that we propose to reduce flood damage in the city of Ain Sefra

for the return periods of 10,100 years. For our study, we proposed the combination of four types of development:

- Raising the retaining walls in the overflow areas, following the 10-year and 100-year flow simulations (from 0.3 to 0.8 cm depending on the overflow areas).
- Building retaining walls in areas that have not benefited from development (right bank of the wadi Tirkount, and left bank and part of the right bank of the wadi Breidj).
- Ecological engineering, by the planting plants in the stream bed, introduced in HEC-RAS by changing of the Manning values ($n = 0.03$).
- Widen the stream bed from their natural form to a relatively rectangular shape and clean up the wadis, because they are used as deposition area of construction rubble and garbage dump. These deposits have the direct consequence of reduction of sections of the wadi. The deposit of garbage dump in the wadi must be forbidden.

The superposition of the flood hazard maps for the two simulated scenarios (before and after proposing developments) (Fig. 15) shows clearly the effect of the proposed developments on reducing the risk of flooding over the city.
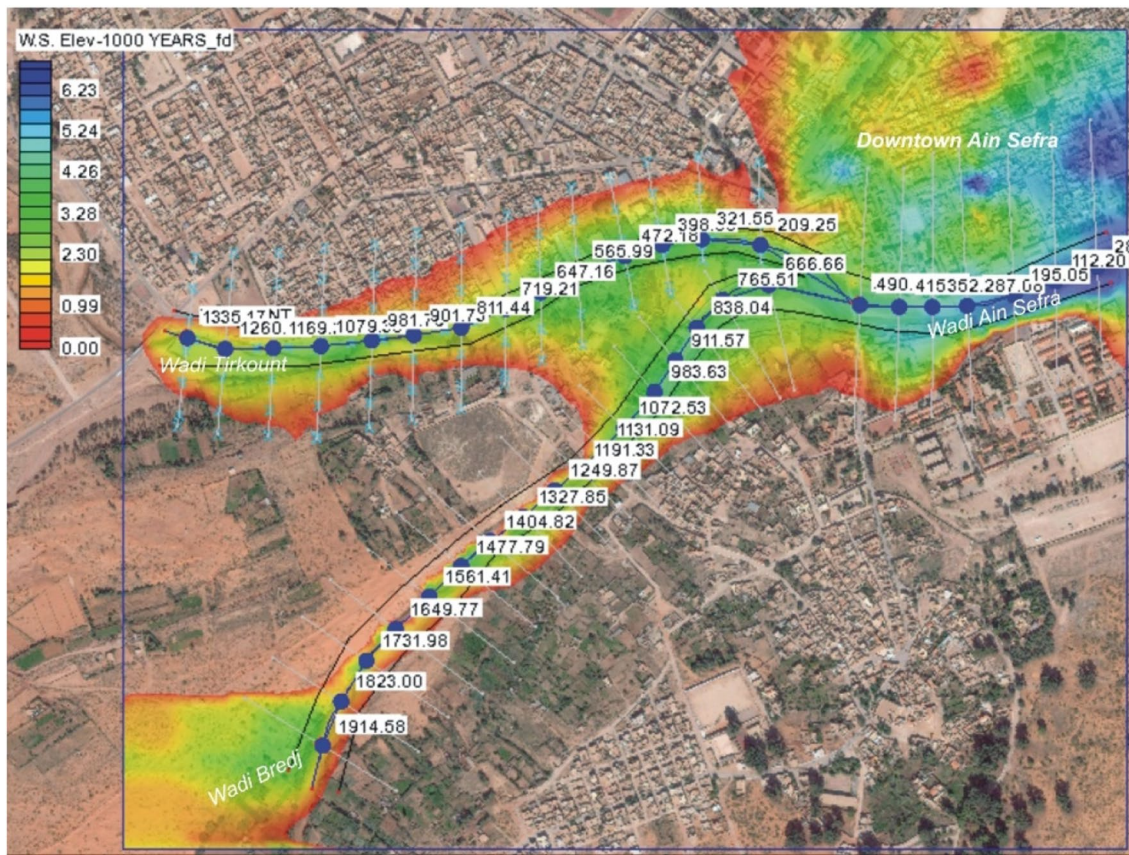
Fig. 10 Flood inundation map in Ain Sefra city (return period 1000 years)

Fig. 11 Retaining walls in wadi Breidj

Fig. 12 Retaining walls in wadi Ain Sefra

The flood inundation map in 3D shows the reassured passage of the 100-year flood at the level of the city of Ain Sefra (Fig. 16). It should be noted that the fact of protecting the city from the risk of all frequencies (1000-year flood for example) is an infinite cost, and the most efficient arrangement is that which ensures the optimum protection against the risk.

Conclusion

Ain Sefra is one of the Algerian cities that had been experienced several devastating floods since the creation of the modern city in 1882. GIS techniques and watershed modeling are highly effective research tools in mapping,
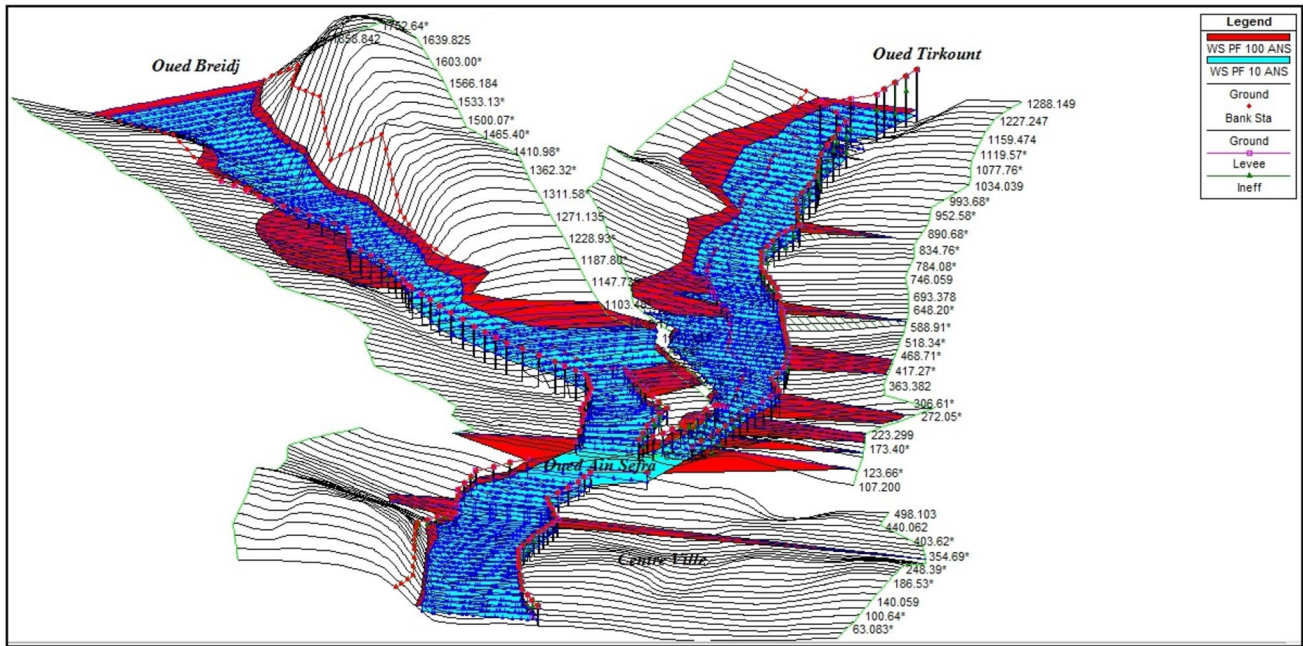
Fig. 13 Flood inundation map in Ain Sefra city in 3D (return period 10 and 100 years)
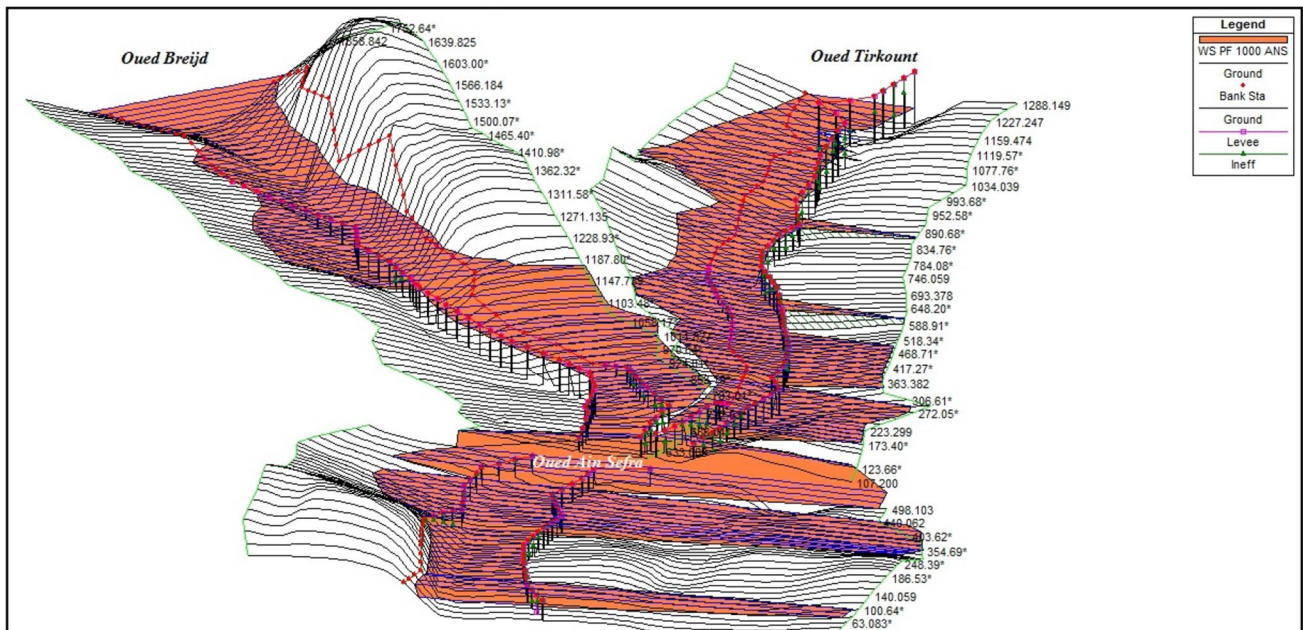

Fig. 14 Flood inundation map in Ain Sefra city in 3D (return period 1000 years)

investigation, and modeling surface runoff, especially in arid regions where lack of proper hydrometeorological data is available. This paper has presented an effective approach to estimate the peak discharge of flows developed from high rainfall events uniformly cover Ain Sefra watershed, and to predict and assess downstream flood hazard by the integration of hydrologic and hydraulic modeling and GIS. The synthesis of the risks related to the floods is based on three principal concepts: hydrological, hydrodynamic, and cartographical. In the hydrological modeling, the HEC-HMS model was applied to Ain Sefra watershed to predict the surface runoff after passing with WMS. The peak discharges obtained for the 10-, 100-, and 1000-year storms are, respectively, 425.8, 904.3, and 1328.3 m^3/s.
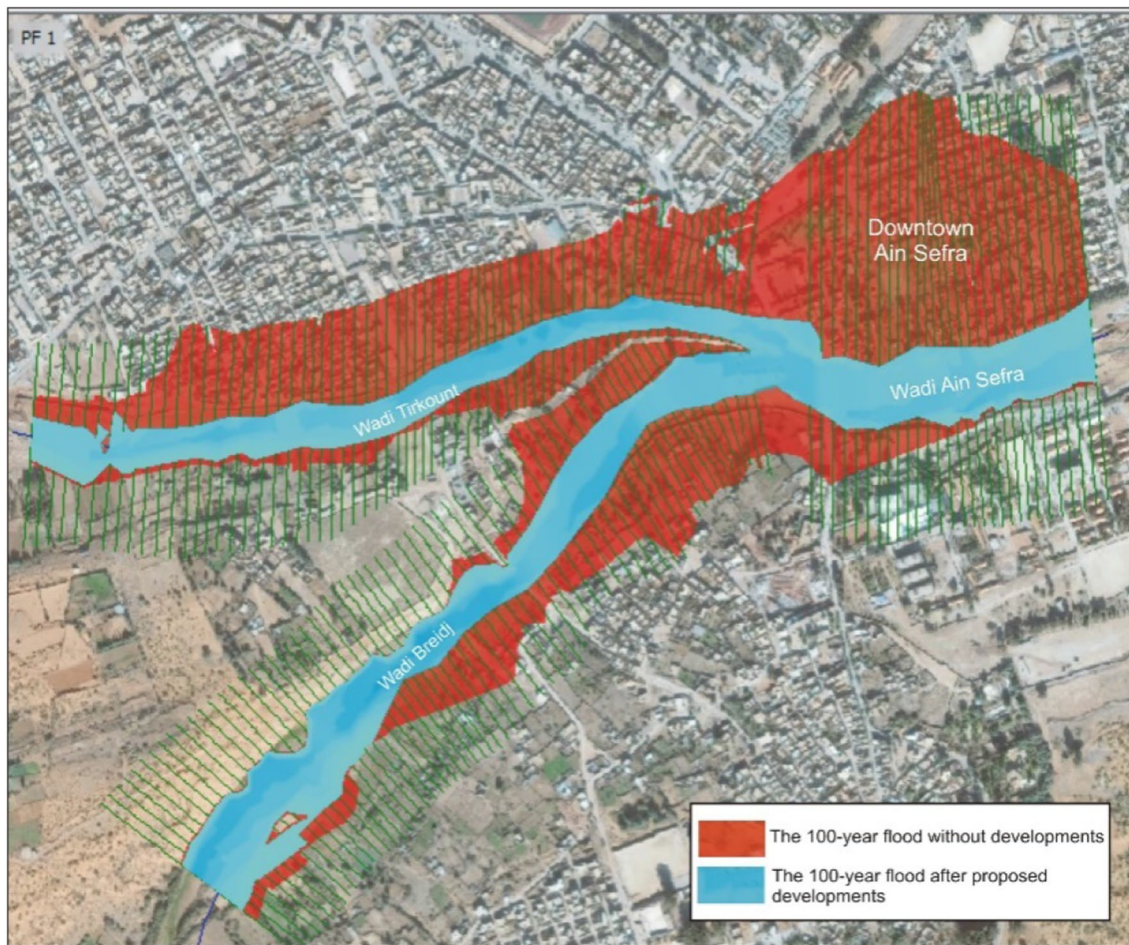
Fig. 15 Flood inundation map in Ain Sefra city (return period 100 years) after and before the proposed developments
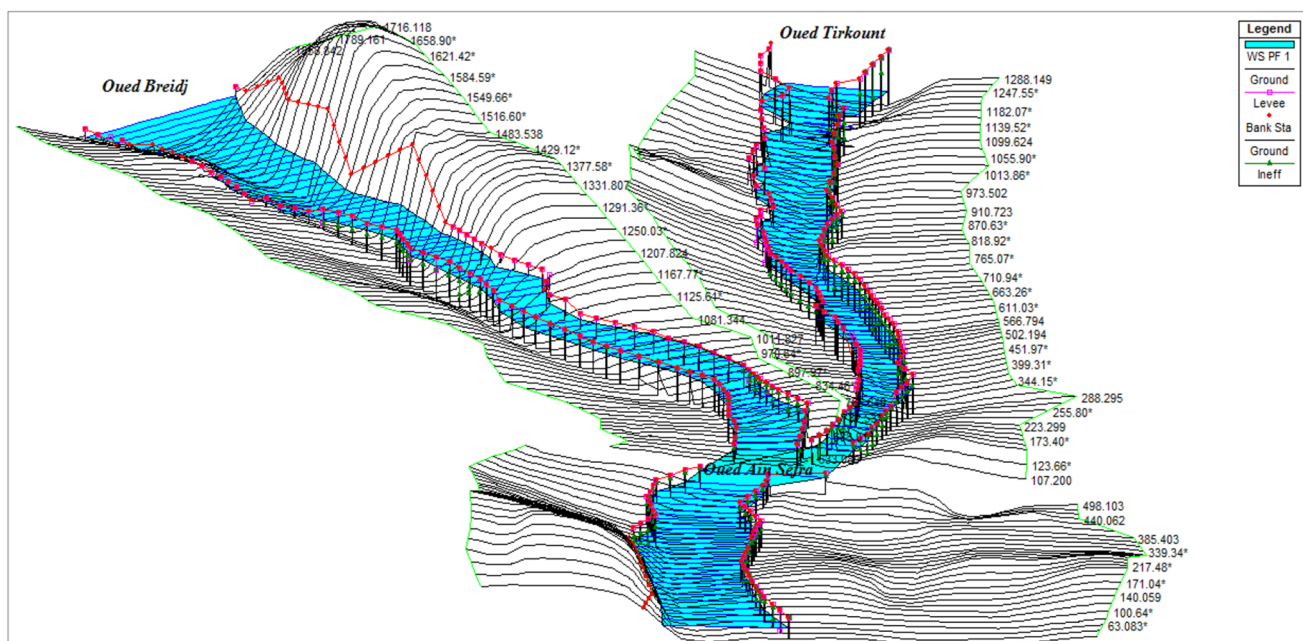

Fig. 16 Flood inundation map in Ain Sefra city in 3D view (return period 100 years) after the proposed developments

The results obtained are very satisfactory. Therefore, run-offs generated by frequency storm method are invaluable for the hydraulic modeling.

The hydraulic modeling carried out by the HEC-RAS model based on the data of the hydrological modeling and on the TIN of the city of Ain Sefra created following the land survey allowed us to highlight several scenarios overflow at the city of Ain Sefra. Flood inundation maps were prepared by considering of concrete retaining walls existence and without it. In this case, three types of simulation are performed:

- For the first simulation, that represents simulation without taking into consideration retaining walls built by local authorities, we remark that the city of Ain Sefra is vulnerable to flooding even for a 10-year flood and the flood zone is expanding from the 10-year flood to the 1000-year flood. This simulation revealed that the region most affected by the flood is the downtown area which represents the junction of wadis Breidj and Tirkount.
- For the second simulation, and to test the performance of concrete retaining walls already built by local authorities in their flood-fight effort. We remark that the retaining walls are generally adequate for 10-year floods, where wadi Ain Sefra has no overflow. However, there are some overflows for the 100-year floods, while the protections done remain insufficient for 1000-year for the three wadis (Breidj, Tirkount, and Ain Sefra). These simulations revealed that the existence of retaining walls resulted in decrease of flood zone area, and so much less lands are endangered by floods, so that environmental effects and damages of flood at the study area decrease clearly.
- The third simulation is based on the diagnosis of hydraulic modeling, which made it possible to target the overflow sites of wadis. The aim is to take into account development proposals that minimize the risk of flooding by taking protection measures along the wadi banks, such as: elevating the retaining walls, creating new protection walls, cleaning the wadis, and recalibrating the minor riverbeds. This simulation is devoted clearly the effect of the proposed developments on reducing the risk of flooding over the city. It should be noted that the fact of protecting the city from the risk of all frequencies (1000-year flood for example) is an infinite cost, and the most efficient arrangement is that which ensures the optimum protection against the risk.

The obtained results have led us to conclude that the simulations made by the chosen models are encouraging. This work is a first contribution to the study of floods in the Ain Sefra watershed. It is a work whose results are a tool for guidance, and decision support to local and regional authorities that accompany the various development projects in the city of Ain Sefra.

To generalize and examine the reliability of the approach followed, the methodology of coupling of hydrological and hydraulic models can be adapted for the use of other catchment area of arid zones. It can form an important tool for the management of flood control and for real-time simulation of inundation in Algeria to prevent or reduce damage in terms of lives, property, and infrastructure. Further research must be done on sediment transport using numerical models, since these models use water depths and velocities as an input.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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