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EVALUATING THE EFFECTIVENESS OF THE EXISTING FLOOD RISK PROTECTION MEASURES ALONG WADI DEFFA IN EL-BAYADH CITY, ALGERIA

BEN SAID M.*, HAFNAOUI M.A., HACHEMI A., MADI M., BENMALEK A.

Scientific and Technical Research Center on Arid Regions, CRSTRA, Biskra, Algeria

(*) bensaid.mosbah@gmail.com

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ABSTRACT

The main cause of flooding in Algeria often arises from water overflowing from the wadis into nearby urban areas. This situation can become even more critical in the arid regions of Algeria, where a prolonged lack of rainfall has been noticeable in recent decades. This has led to decreased flow in these wadis and, consequently, an increase in human activities encroaching upon the dry areas near the wadis. As a result, this has given rise to exceptionally severe catastrophic events. El-Bayadh city is among several cities in the region that have experienced multiple destructive floods. This paper focuses on the October 1, 2011 event in El Bayadh. The event was numerically replicated through hydrological and hydraulic modeling using HEC-HMS and HEC-RAS software. The modeling process included the influence of key structures such as protective walls, channels, and buildings, which are commonly neglected in similar flood modeling studies. This enhanced model incorporates real-world complexities, leading to a more accurate representation of the flood scenario. Utilizing the calibrated model, the performance and capacity of the channel and protective structures in safeguarding the city's nearest buildings were assessed. The analysis demonstrated that the October 1, 2011 occurrence, with a peak discharge of 425 m^3/s, greatly exceeded the channel's capacity, which can only handle a peak discharge of 180 m3/s.

Keywords: Flood risk, Arid regions, Flood control, Hydraulic modeling

INTRODUCTION

Flooding has impacted numerous countries across the globe, resulting in a substantial loss of life and extensive damage to structures and infrastructure. In the past decade, there has been a noticeable rise in both the severity and frequency of such extreme events (Aroua, 2020; Nofal et al., 2021; Hafnaoui et al., 2023), and it is anticipated that future flood risks will continue to escalate due to climate change and alterations in land use (Juárez et al., 2021). In arid regions where precipitation is scarce and extended dry spells are common, there have been substantial losses in terms of both human lives and properties due to severe flooding (Lin, 1999; Abd Rahman et al., 2023; Zeggane et al., 2021). This natural phenomenon occurs as a result of intense rainfall over a short period, leading to high-velocity, short-duration flows with sharp peaks. Moreover, the heightened capacity for flooding to cause destruction in arid and semi-arid regions is exacerbated by the presence of debris and the extensive transportation of large sediment quantities. These phenomena are primarily attributed to the combination of loose soil and inadequate vegetation (Nabinejad, 2023). In the arid and semi-arid regions of Algeria, there have been several instances of erratic climatic phenomena leading to significant loss of life and extensive property damage, especially in recent years. For example, in 2004, Adrar faced challenges. In 2008, both Ghardaïa and Bechar encountered severe conditions. Ghardaïa experienced a severe climatic event in 2008, resulting in the loss of 100 lives. Bechar also faced adverse weather conditions in the same year, which led to the loss of 8 lives. In 2011, El Bayadh faced a climatic challenge that resulted in 13 fatalities. The following year, in 2013, Adrar experienced significant issues. In 2014, Ain Sefra also witnessed erratic climatic phenomena, leading to property damage and loss of life. In 2015, Tamanrasset and Tindouf were also affected by this phenomenon. Moreover, in 2023, El Bayadh found itself facing similar challenges, with 4 lives lost. To provide an example of the economic and financial impact of such events in these regions, during the flooding of 2008, the cost of material damages in Ghardaïa amounted to approximately 20.1 billion Algerian Dinars (Yamani et al., 2016). In these regions, where most cities and agglomerations are intersected by wadis, people's lives and properties are significantly at risk, particularly during the wet season. These risks are primarily a result of the erratic wadi flow, with these areas commonly having dry wadi beds for most of the year. Due to climate change, there has been a prolonged absence of significant water flow in numerous wadis, primarily due to the repeated and severe droughts, resulting in the disappearance of multiple segments of wadis channels (Pang and Tan, 2023). Consequently, many residents in these areas have extended their construction and activities into high-risk zones. These regions are grappling with a significant data shortage, which poses a challenge to the study of hydrological processes and assessment (Yamani et al., 2016; Lahmar et al., 2021). Nonetheless, numerous researches have been undertaken to mitigate the repercussions of such significant occurrences. Therefore, to reduce flooding damages in Skikda (Algeria), Boulghobra (2013) proposed a relevant integrated management plan of three functions.

The study carried out by Gassi and Saoudi (2023) examined for the first time the impacts of the different physical parameterization schemes in the Weather Research and Forecasting (WRF-ARW) model on the quality of heavy rain prediction during the transitional season in eastern Algeria. Various physical model configurations were examined and verified by considering 144 numerical experiences using different combinations of cumulus and microphysical schemes compared to rain records of a network of thirty specialized meteorological stations for the period from August 1 until the last of October 2022.

Kapadia et al. (2023) state that one of the most damaging natural disasters that occurs anywhere in the world is flooding. The authors add that flood hazard mapping is essential to determining the flood risk zone areas. In their study, the analytical hierarchical process (AHP) and geographical information system (GIS) were used for flood hazard mapping of the lower Damanganga River basin from the Madhuban Dam to the Arabian Sea.

The main aim of the study, carried out by Baudhanwala et al. (2023), was to simulate the existing stormwater drainage system and to identify any overflowing manholes in the west zone of Surat City (India) by employing the Storm Water Management Model (SWMM). The authors state that SWMM is an effective tool for simulating urban floods. During the study, rainfall data for 2018, 2019 and 2020, and stormwater network data, were used to evaluate the current stormwater drainage network.

Zegait and Pizzo (2023) focused on a new program created in Visual Basic for Applications (VBA) to supply parameters for sizing a damping reservoir to control floods. This program will be applied to the IDLES basin in southern Algeria, where many devastating floods are known. The chosen approach involves a selection of the most vulnerable location for the flood. These hydrological flow data have been calculated according to the empirical approach producing a higher flow rate to the maximum permitted for the streambed, where flood routing is used to size the reservoir.

In the study by NG et al. (2022), it is stated that weirs are widely used for controlling the flow discharges and water levels of a bifurcated river for flood risk reduction. In this study, a one-dimensional (1D) numerical model of the Hydrological Engineering Centre - River Analysis System (HEC-RAS) has been applied to simulate an idealized channel with the applications of various weir geometries at various locations. The model has been set to simulate a U-shaped main channel with two identical U-shaped bifurcated channels. Simulations have been undertaken for the weirs with cross-sectional shapes of rectangular, Cipolletti (trapezoidal), and V-notch (triangular).

The main objectives of the study by Ayari et al. (2016) were to simulate the local flows of Medjerda in flooding, map the exposed issues, and quantify the flood risk. The hazard was evaluated with the help of a two-dimensional hydrodynamic model: the SMS model. The Analytic Hierarchy Process (AHP) was used to quantify the vulnerability. Flood risk maps were finally obtained by crossing the flood hazard map and the vulnerability map of the exposed issues.

In their relevant study, Nezzal et al. (2015) reveal that the watershed of the Hamiz Wadi in Algeria, in its downstream part, has recorded frequent flooding with high amplitude in recent years. This basin presents natural physical factors of predisposition to flooding. The frequency analysis of the average bed's flow rates and submersion heights indicates a ten-year return period for floods. The occupation of the natural flood expansion zone by various forms of habitats causes a dysfunction of the Wadi. The population and habitats already vulnerable by their precariousness are the most exposed to heavy flooding. The established risk mapping can constitute a guidance tool for communities in the redevelopment plan for this Wadi, and even for other Wadis.

Hafnaoui et al. (2009, 2013) conducted research in Doucen (Algeria), an arid region within Biskra. They assessed the combined impacts of climatic (e.g., rainfall) and morphological (e.g., topography) factors on flood events and generated flood vulnerability maps for the area.

Using instantaneous flood data from the Foum El Gherza station in Biskra (Algeria), Hachemi (2016) employed Flood Frequency Analysis (FFA) to create a flood-duration-frequency (QDF) curve. They suggest these designed flood hydrographs serve as valuable input for hydraulic modeling and simulations in flash flood-prone regions.

On the other hand, Benkhaled et al. (2013) analyzed the temporal distribution of flood events recorded between 1950 and 2010 in Biskra (Algeria). Data archive was used to describe some characteristics of floods such as peak discharge, and duration. Examination of data shows a peculiar seasonality effect on flood occurrence, with events mostly occurring in autumn.

Note the study of Balkissoon et al. (2033) where a triangulated grid was used to estimate the areal precipitation for regions in Trinidad. The rain gauge stations, from three hydrometric units, served as nodal points. Three parameters, nodal rainfall, and its x and y coordinate, were used to determine the areal precipitation through linear interpolation. Thereafter, the total elemental volume of rainfall and the elemental average rainfall precipitation were determined. To estimate the areal precipitation of the grid for each month, a decadal (2006-2015) average of the monthly rainfall values were calculated.

Numerous hydrological investigations have utilized the Hydrologic Modelling System HEC-HMS, integrated software developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC), specifically designed as a modeling tool for all hydrological processes within dendritic watershed systems. This popularity arises from its adeptness in simulating runoff across various temporal scales, be it short or long-term events, its user-friendly interface, and utilization of common methodologies (Tassew et al. 2019). In their study, Hussain et al. (2021) utilized the HEC-HMS Model to simulate flow in tributary catchments within the Kaohsiung area of Taiwan. Their findings suggest that this methodology exhibits promise for application in ungauged catchments for water resources management and planning, especially amidst future climate scenarios. Nadeem et al. (2022) utilized HEC-HMS for flash flood forecasting and risk management in a small watershed in Hazara, Pakistan. Their observations indicate that the HEC-HMS framework proves to be an effective tool for flood forecasting. Yu et al. (223) investigated the suitability of the HEC-HMS model for flood simulation in urbanized basins and assessed the impact of land use changes on catchment runoff. Their findings reveal that the HEC-HMS model is well-suited for an urbanized basin, with its performance being superior before urbanization compared to after urbanization. Many researchers have utilized the HEC-HMS model to investigate hydrology in arid and semi-arid regions. For instance, Norhan et al. (2016) employed the HEC-HMS model to replicate rainfall-flow dynamics within an arid environment at Wadi Alaqiq, Madinah, Saudi Arabia. They affirmed that the model's outcomes are suitable for rainfall-runoff scenarios and hold potential for managing wadi corridors in arid regions. In 2022, Laassilia et al. employed the HEC-HMS software for numerical modeling to investigate event-based flow hydrograph patterns within a semi-arid region of Morocco. Their study revealed that utilizing hydrologic modeling through HEC-HMS has yielded promising and satisfactory outcomes, particularly in the context of flood estimation within arid and semi-arid regions. Similarly, Ramadan et al. (2022) employed a combined GIS-WMS-HEC-HMS approach to develop a flood hazard model for Wadi Sudr, Egypt. Beslimane et al. (2020) simulate floods in urban zone by applying a calculation code solving the two-dimensional Saint Venant equations. The obtained results were compared with the different available collected data. Derdour et al. (2018) focused on modeling rainfall-runoff relations using HEC-HMS in a semi-arid region of the Ain Sefra region, Algeria. Based on their results, such as the Nash-Sutcliffe efficiency of 0.95, they suggest the model's potential for similar applications. Hydrologic data generated by HEC-HMS can be integrated into hydraulic models. This coupling provides valuable insights for assessing the effectiveness of flood protection projects for communities and properties (Onuşlüel et al., 2010). This coupling is often achieved through HEC-RAS, US Army Corps of Engineers software for river and stream hydraulic modeling. This combined approach, as demonstrated by Sharif et al. (2014) in their investigation of flood hazards in a rapidly urbanizing Riyadh watershed, offers valuable insights for flood protection projects. By employing both HEC-HMS and HEC-RAS software, they were able to not only identify flood hazard zones, but also pinpoint streets likely to be affected by flooding.

Abdulrazzak et al. (2019) also employed HEC-HMS and HEC-RAS to assess flash flood risks in an urban arid environment within Saudi Arabia. Their study focused on the impact of inundation depths on the flood channel and floodplain for various flood scenarios. Utilizing HEC-HMS for hydrologic modeling and 2D HEC-RAS for hydraulic modeling, they delineated inundation areas corresponding to different flood hazard levels. Similarly, Al-Hussein et al. (2022) employed HEC-RAS and HEC-HMS to investigate the floodplains of the Khazir River in Northern Iraq, aiming to mitigate recurrent flooding issues. Through their analysis, they were able to identify areas with differing levels of impact. Their findings revealed a robust correlation between HEC-HMS and HEC-RAS, facilitating the assessment of flood risks and the precise prediction of future floods in the research area.

In 2016, Yamani et al. employed this methodology to study the hydrological reaction of the Wadi M'zab watershed in Ghardaia, Algeria, to a precipitation event. Using the HEC-HMS model for hydrological analysis and HEC-RAS 1D for hydraulic modeling, they assessed the expanded flood-prone zone, resulting in the development of flood vulnerability maps. They assert that their study yielded positive outcomes in replicating a particular flood event, suggesting the applicability of their method for examining floods in comparable arid regions. Otmani et al. (2022) also employed hydrological and hydraulic models to analyze a flash flood event in Wadi Deffa, Algeria. They utilized volunteered geographic information (VGI) data, a valuable resource in scenarios like the El-Bayadh flooding where traditional hydraulic data is lacking. VGI data aims to offer comprehensive geo-localized information about the disaster area. Comparing various models using VGI data, they determined that the EBA4SUB-FLO-2D approach performed better than others in simulating flood areas. The study suggests that this modeling approach can provide reliable data for managing flood risks in ungauged watersheds in southwest Algeria. Hafnaoui et al. (2020; 2022) conducted a study with the objective of producing a flood hazard map for El Bayadh city. They achieved this by utilizing data associated with rainfall and employing the ArcGIS and HEC-RAS software. The authors emphasize the intended complementary role of the map to weather warnings in enhancing flood protection efforts. It facilitates decision-makers in making swift choices to protect against potential flooding. El-Bayadh, the focus of this study, has repeatedly faced severe flooding, notably in 2008, 2011, and 2023. The most catastrophic event occurred on October 1, 2011, when the Deffa Wadi overflowed, unleashing its destructive force on nearby houses and structures despite existing protective measures. The channel and protective barrier proved incapable of containing the volume of water, causing it to carry away everything in its path, particularly the nearest houses and structures situated along its main course. Remarkably, this catastrophic event unfolded following a rainfall of 60 mm within a mere hour and a half, causing over 13 lives to be lost, and extensive damage was documented. The aim of this paper is to reproduce the El-Bayadh flooding incident using hydrological and hydraulic modeling techniques, utilizing HEC-HMS and HEC-RAS. This involves integrating main structures that could affect flow in the area, such as protective walls, channels, and buildings which are often overlooked in similar flood modeling studies. Additionally, it seeks to assess the effectiveness and capacity of existing flood risk management structures.

STUDY AREA

Elbaydh city is situated in the southeastern part of Algeria, spanning from 33°38'00" to 33°46'00" N latitude and 00°59'45" to 01°09'50" E longitude (Fig. 1). Like numerous other cities located in the arid regions of Algeria, Elbaydh is intersected by the Wadi Deffa, which drains a watershed covering approximately 106 square kilometers and is prone to causing significant and devastating floods. A protective canal was established adjacent to the wadi channel to provide defense against flooding for the nearby residents and their properties. This safeguarding initiative involved the construction of reinforced concrete walls, standing at a height of 6 meters. The width of the canal varied, ranging from over 50 meters to as narrow as 11 meters, depending on specific locations and available space, taking into account the presence of residential structures along the riverbanks.

The study area exhibits significant climatic variations across seasons, primarily characterized by distinct dry and wet seasons, often accompanied by frequent snowfall, which result in noticeable differences in both rainfall and temperature between winter and summer months. According to Madi et al. (2023), the average maximum temperatures reach 28 °C in July and August, while December and January experience an average low temperature of 5 °C. The annual mean precipitation ranges from 200 to 300 mm, with the majority occurring between September and May. July stands out as the driest month, often receiving no rainfall at all, whereas March typically receives the highest amount of precipitation.

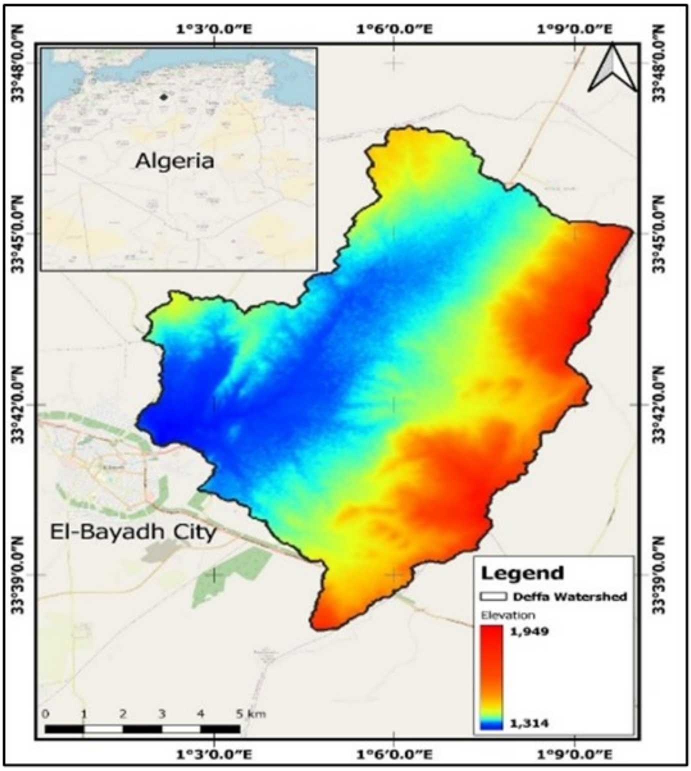

Figure 1: Map indicating the location of Wadi Deffa watershed

DATA COLLECTION AND METHODOLOGY

The methodology employed in this study for analyzing flood risk involves data collection, hydrological modeling, and hydraulic modeling. The specific steps are detailed in Fig. 2. The primary challenge in these areas lies in the lack of data. For the events that occurred on October 1, 2011, the available information is limited to precipitation data, which amounted to 60 mm over 1 hour and 30 minutes. The flood event occurred at approximately 17:30, and information about the affected area was provided by local authorities. QGIS version 3.22 was utilized to extract and prepare the initial data, such as the Digital Elevation Model, land cover, and soil type. In this case, the SRTM Digital Elevation Model (DEM), characterized by a 30-meter resolution and acquired from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/), and the imagery from Copernicus Sentinel-2, with a resolution of 10 meters, were considered in the process.

Table 1: Main Attributes of the Deffa Basin

Parameters	Values
Longest Flowpath Length (KM)	19.15973
Longest Flowpath Slop	0.02597
Centridal Flowpath Length (KM)	6.24072
Centridal Flowpath,Slope	0.00569
10-85 Flowpath Length (KM)	14.36979
10-85 Flowpath Slope	0.00526
Basin Slop	0.10414
Basin Relief (M)	631
Relief Ratio	0.03293
Elongation Ratio	0.60643
Drainage Density	0.38409

The HEC-HMS software version 4.10, developed by the Hydrological Engineering Center was selected for the hydrological modeling process. HEC-HMS is a physically-based semi-distributed model created by the US Army Corps of Engineers, designed to simulate rainfall-runoff processes within watershed systems. This model has gained widespread application in numerous hydrological studies due to its ability to simulate runoff in diverse environments. Operating as both a lumped and distributed rainfall–runoff model, HEC-HMS accommodates a variety of hydrologic scenarios in both small and large catchments. Furthermore, it proves beneficial for conducting water balance studies and assessing the effects of land use and climate change on runoff generation. Additionally, the software plays a crucial role in addressing issues associated with flooding (Cuomo et al., 2021). The HEC-HMS software comprises a comprehensive suite of hydrological modeling components organized into four distinct sub-models. These sub-models collectively facilitate the simulation of the rainfall-runoff process in watersheds. The key components are as follows: the Basin Model, which encapsulates the physical characteristics and hydrological properties of the watershed or basin under consideration; the Meteorological Model, focusing on capturing atmospheric conditions that influence the hydrologic cycle; Control Specifications, referring to the set of rules and parameters governing the simulation process; and Time-series Data, a fundamental aspect dealing with the representation and utilization of temporal data, including historical records and observed data. The initial phase of the hydrological process involved employing HEC-HMS to extract essential details from the Digital Elevation Model (DEM) of the designated catchment area. This included information on drainage networks, catchment boundaries, flow paths, slopes, and reach lengths, as outlined in

Table 1. Subsequently, this information, along with meteorological data, was utilized to replicate the hydrograph of the event on October 1, 2011, in the Deffa Wadi watershed. For this end different steps and equations.

The Soil Conservation Service (SCS) Curve Number (CN) method was employed in this study to estimate the direct runoff from the rainfall event. The SCS-CN model calculates effective rainfall or direct rainfall by taking into account cumulative precipitation, land cover, soil characteristics represented by the Curve Number, initial abstraction, and maximum retention. The model incorporates these parameters into equations that simulate the runoff process, providing an estimate of the effective rainfall contributing to direct runoff in a watershed, as shown in the equations (1) and (2):

(1)

Here, Pe represents the direct runoff (mm), P (mm) indicates the depth of precipitation accumulated at time t (s), and S (mm) denotes the maximum potential retention (cm), reflecting the upper limit of soil moisture capacity. This capacity is computed based on the curve number (CN), as indicated in equation (2):

(2)

The SCS unit hydrograph method was utilized to simulate the runoff response of the watershed, with the objective of modeling its hydrological behavior. This method necessitates a lag time parameter, as described in equation (3), defined as the duration between the centroid of precipitation mass and the peak discharges. The latter includes the concentration time parameter, which can be computed using the Kirpich method outlined in Equation (4).

(3)

(4)

Where, Tc represents the concentration time (in minutes), L denotes the length of the primary river (in meters), and S stands for the average slope of the main river (in meters per meter). Following that, the output of the hydrological model, which is the hydrograph, was utilized as input for conducting hydraulic modeling using the HEC-RAS 6.2 software created by the US Army Corps of Engineers. A modification to the terrain was implemented within HEC-RAS to accurately depict the geometry of the real-world scenario. In this situation, the model encompassed the development of a channel, defensive barriers, bridges, and the closest structure. For predicting flow characteristics, two-dimensional hydraulic configurations were utilized, employing a grid resolution that ranged from 10×10 m for areas distant from the main stream flow to 3×3 m to capture detailed flow behavior near structures, such as protective walls. The choice of cell size was a compromise between computational time and precision. Initially, the occurrence on October 1, 2011, was replicated both hydrologically and hydraulically. Given the absence of available observed flow data, the calibration process relied on utilizing flood inundation extent data collected by the local agency promptly after the event. Following these steps, a numerical estimation was utilized to determine the capacity of the established channel designed to protect nearby residents and their properties from potential overflow from the Deffa Wadi. Subsequently, the peak discharge for the current channel configuration was identified.

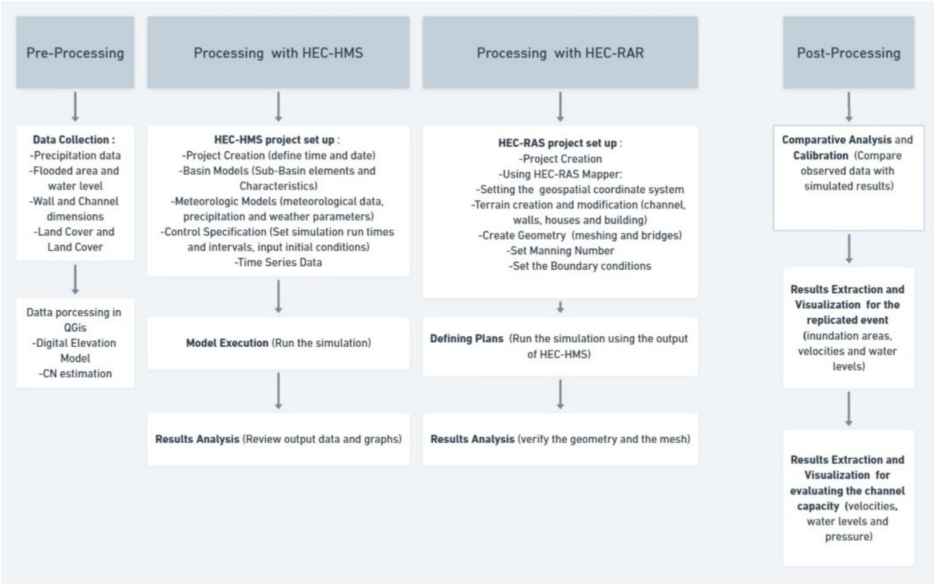

Figure 2: Flowchart showing the Applied Methodology Workflow

RESULTS AND DISCUSSION

Recreating the Event and Calibration

The incident on October 1, 2011, was recreated utilizing the available data. This disastrous occurrence occurred following an intense rainfall of 60 mm within just an hour and a half, as reported by local authorities. According to the available information, primarily from eyewitness accounts of citizens and published recorded videos, the flooding began at 17:30. Initially, HEC-HMS software is employed to conduct rainfall runoff modeling, evaluating the watershed response of Deffa Wadi. The hydrograph is specified at the location where the Wadi enters the urbanized zone of El-bayadh City, signifying the watershed outlet. Throughout the analysis, the basin was treated as a single entity, and it is assumed that the entire watershed will receive the same amount of design rainfall (Fig. 3).

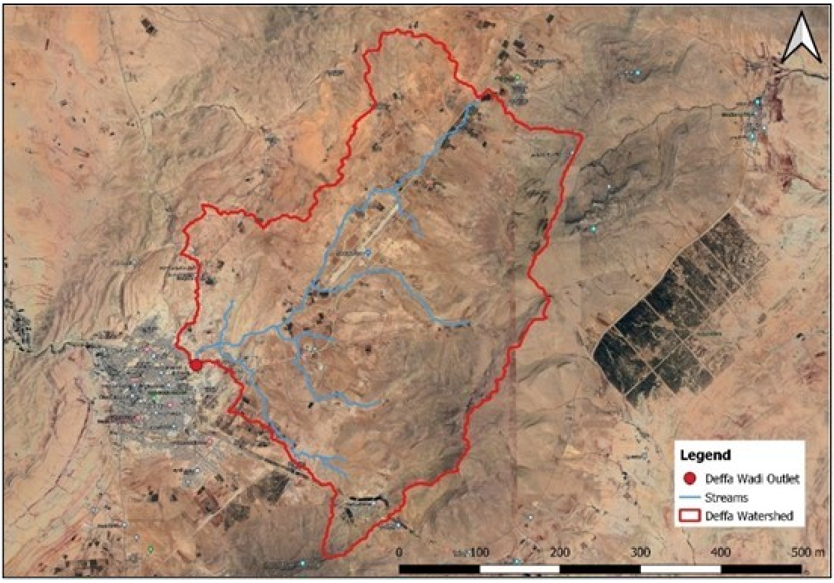

Figure 3: Deffa watershed delineation and stream network with outlet

To more accurately emulate real-world conditions, the recommended parameters were employed in accordance with the recommendations of the local agency. Specifically, a precipitation amount of 60 mm was distributed over an hour and a half, based on information provided by the local authority. A time of concentration of 3 hours was applied, as suggested by the local agency. The estimated value of the curve number (CN), derived from the land cover, land use, and soil data of the Deffa Wadi watershed, was determined to be approximately 77. The hydrograph derived by inputting the aforementioned values into the HEC-RAS software for hydraulic modeling. In this case, resulted in an underestimation of the flooded area extent when compared to the observed data. Consequently, calibration was carried out by adjusting the curve number (CN), as it proved to be the most influential parameter. A value of 91 was identified as the most suitable for achieving more precise results. Indeed, utilizing a CN value of 91 enables the attainment of a peak discharge value that closely aligns with the locally estimated peak flow of approximately 450 m^3/s. Moreover, the CN value employed in this scenario is relatively close to the range of CN values, between 85 and 86, estimated by Derdour et al. (2018) in their study conducted under comparable soil and land-use conditions. This outcome leads to a peak flow of 424.7 m^3/s and a volume estimate of 37.73 m^3, as illustrated in Figs. 4 and 5.

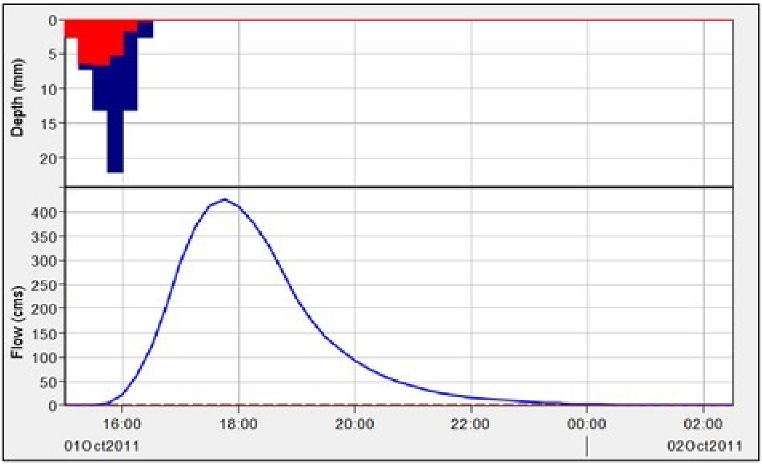

Figure 4: Flood Hydrograph for the Rainfall Event on October 1, 2011

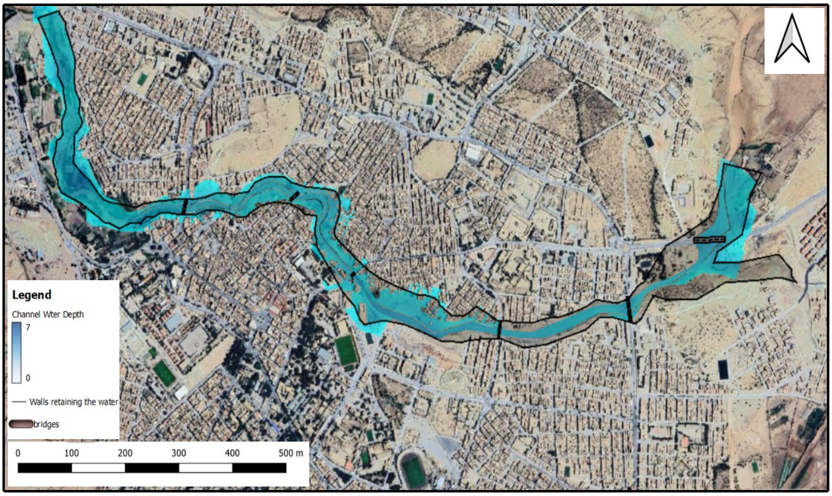

Figure 5: Comparison between the simulated and observed data

Channel capacity estimation

A replication of the October 1st, 2011 flood event revealed that the flooding primarily impacted the El-Bayadh city center. As shown in Fig. 6, both observed and estimated water levels in the city center reached approximately 5 meters. An important observation from Fig. 6 is the variation in channel width. The cross-sectional area gradually diminishes as the channel moves from upstream towards the city center. This reduction is significant, with the average width decreasing from 50 meters upstream to only 11 meters in the city center. Notably, this localized narrowing corresponds with the area of highest flood risk. Hafnaoui et al. (2022) presented a historical land use change analysis spanning in El-Bayadh city from 2003 to 2019. They concluded that urban expansion has resulted in a reduction in the cross-sectional area of the Wadi, making certain areas more susceptible to flooding.

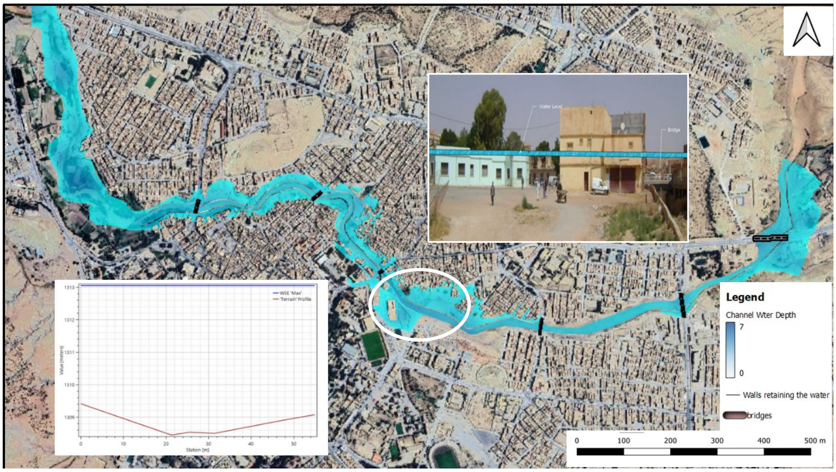

Figure 6. Observed and simulated water levels at the restricted section of the channel at a flow rate of Q = 450 m^3/s.

While a flood wall of 6 meters in height and channelization are in place to protect the city and urban areas along Deffa Wadi, their effectiveness is questionable. Observations during flood events indicate that floodwaters have overtopped the walls, highlighting the potential inadequacy of the current protection measures. Consequently, it is important to evaluate the effectiveness of the existing channel and protective structures in safeguarding citizens, their properties, and activities from potential overtopping of Deffa Wadi. In this context, an analysis of multiple input hydrographs to determine the maximum capacity was conducted. Additionally, a separate simulation was conducted specifically to understand how the presence of bridges influences the behavior of the channel during flood events. Bridges can act as obstacles, potentially impacting water flow and increasing flood risk.

Impact of bridges presence on maximum channel capacity

As previously highlighted, the efficacy of the existing Deffa Wadi channel and protective structures in safeguarding citizens, their properties, and activities from overtopping necessitates evaluation. In this context, an evaluation was conducted using multiple input hydrographs to assess the maximum channel capacity of the channel while accounting for the presence of bridges. Fig. 7 depicts a hydrograph with a peak discharge of 180 m^3/s, representing the channel capacity of Deffa Wadi.

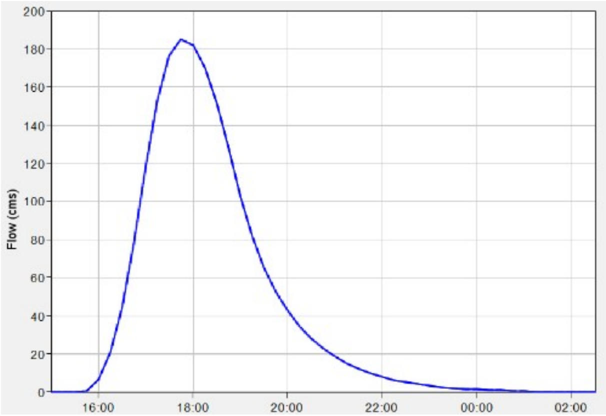

Figure 7: hydrograph conforming to Deffa Wadi's channel capacity

The incorporation of this hydrograph into the hydraulic model demonstrates that the channel can evacuate without experiencing overflow (Fig. 8). For an analysis of flow variations within the city, water levels were assessed at three points: upstream of the city center, at the city center, and downstream of the city center. These water levels were determined under a scenario featuring a peak flow rate of 180 m^3/s. The outcomes are illustrated in Fig. 8. Under such conditions, it is evident that the water level upstream and downstream does not reach the crest of the channel. However, at the city center, the water level reaches the maximum capacity of the channel.

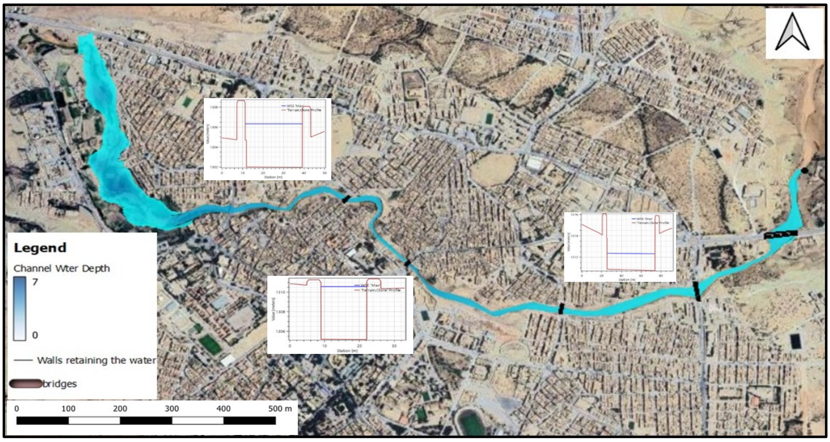

Figure 8: Channel capacity at flow rate Q = 180 m^3/s

Effect of bridge removal on maximum channel capacity

To specifically analyze the influence of the bridges on the flow dynamics of Deffa Wadi's channel, the assessment was performed under conditions where no bridges were present. For that reason, the hydraulic model utilized the hydrograph extracted from the October 1, 2011 event to examine the impact of the bridge on flow behavior during the flooding of Deffa Wadi. Fig. 9 demonstrates that the channel capacity, without bridges, is sufficient to handle the October 1st, 2011 flood event without overflowing, particularly within the city. This confirms that the presence of bridges within the Deffa Wadi channel contributes to flooding, highlighting their considerable influence on channel flow behavior. An assessment of flow variations within the city was conducted by measuring water levels at three key points: upstream of the city center, at the city center itself, and downstream of the city center. The water level remained below the channel's crest both upstream and downstream of the city center. However, the water level within the city center reached its maximum (Fig. 9).

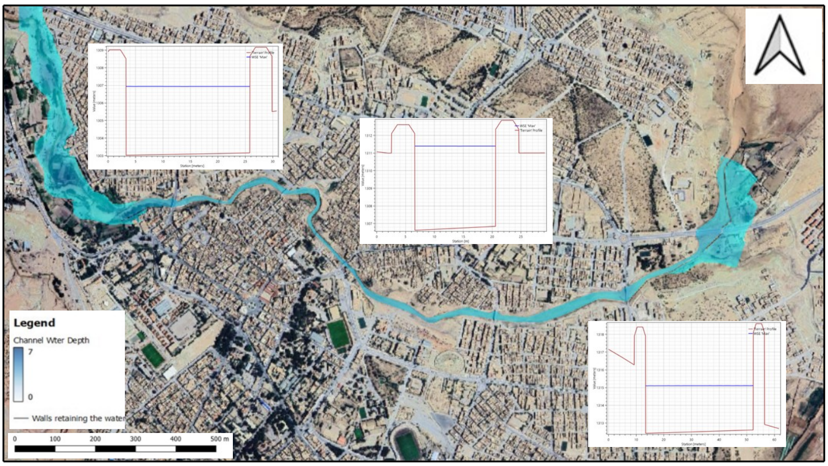

Figure 9: Channel capacity without bridges at flow rate Q = 450 m^3/s

The obtained results raise significant concerns. With the current channel capacity, the city would be unable to handle a discharge even close to the 450m^3/s experienced during the October 1st, 2011 event. This poses a considerable risk to the safety of residents and their properties. As previously noted, the narrowing of the natural channel section resulting from land use changes; is one of the main factors contributing to the heightened risk of flooding in arid regions, as indicated by Hafnaoui et al. (2022). It's essential to recognize that the flow paths (wadis) in the arid regions are exceptionally wide. This is primarily due to the specific flooding patterns in these areas, which frequently result in rapid flash floods. As a result, the width can exceed 1 kilometer in some cases (Remini, 2020; Remini, 2023). However, many of these wadis, particularly those located within or near cities, are experiencing changing conditions that render them vulnerable to encroachment and reduced capacity. This encroachment, often driven by the expansion of buildings and activities within the wadis' path, reduces the space available for natural channels, potentially increasing flood risks. Two primary elements may contribute to this encroachment on wadi channels, potentially leading to catastrophic human casualties and material losses.

Firstly, in regions characterized by arid climates featuring infrequent rainfall and prolonged dry periods, the natural channels of wadis, also known as ephemeral rivers, often resemble dry land. As water flow availability decreases, especially in recent years, certain wadi channels have undergone contraction or even disappearance. This troubling development has attracted people into settling and engaging in activities within the wadi beds, mistakenly viewing them as safe terrain. However, this poses a significant risk when heavy rains, particularly extreme events, inevitably return. Secondly, the construction of the protection walls may have been based on insufficient data, not only leading to an underestimation of required capacity, but also creates a false sense of security, further encouraging encroachment within high-risk areas, ultimately amplifying the magnitude of the overall risk.

The results also indicate that the channel capacity, in the absence of bridges, can accommodate the October 1st, 2011 event or similar events without facing any problems.

As it is shown from the obtained data for the channel capacity without the presence of bridges, it can comfortably accommodate the October 1st, 2011 event, particularly along the channel within the city, without encountering any issues. While these initial findings provide valuable insights, further analysis is crucial to achieve even greater accuracy. This could involve employing 3D modeling or experimental models, if they are available. The significant difference in channel capacity with and without bridges underscores the substantial impact bridge presence has on Deffa Wadi's flow behavior, particularly within the city center (Fig. 10). Bridges can significantly diminish channel capacity through various mechanisms. Firstly, the presence of bridge piers and abutments diminishes the available flow area, restricting the passage of water and ultimately limiting the channel's overall capacity. Secondly, turbulence and friction generated by bridge structures slow down the flow of water, resulting in a decrease in channel capacity. Additionally, the disruption of flow patterns caused by bridges can lead to erosion around piers and sedimentation downstream, further diminishing the channel's capacity to handle water flow. Lastly, bridges may contribute to upstream water buildup, especially during high flow conditions, consequently lowering the channel's capacity to accommodate additional water volume.

Until now, the reasons behind the failure of the Deffa Wadi Canal to mitigate the floods of October 1, 2011 remain unclear. Was its construction based on inaccurate data, especially in regions that suffer from a scarcity of data and information? As a result, the canal's drainage capacity was limited, and it was mistakenly believed that the size of the canal was sufficient, particularly since water flow in the Wadi channel in recent decades is rare, and urban expansion prevented further enlargement by encroaching upon the natural path of the valley. Alternatively, the initial canal design could have been sufficient for floodwater volume. However, bridges might have been built without proper hydraulic considerations, reducing the channel's ability to handle water flow. Perhaps the original number of bridges proved inadequate, requiring later additions for population growth. Unfortunately, these expansions might not have been accompanied by updates to the canal's hydraulic capacity. These possibilities still exist, but what is certain is that the current state of the canal and the protective structures are still insufficient to safely manage floods such as those that occurred on October 1, 2011, or any similar floods. Urgent intervention is necessary to prevent recurrence of past disasters, and to protect lives and property.

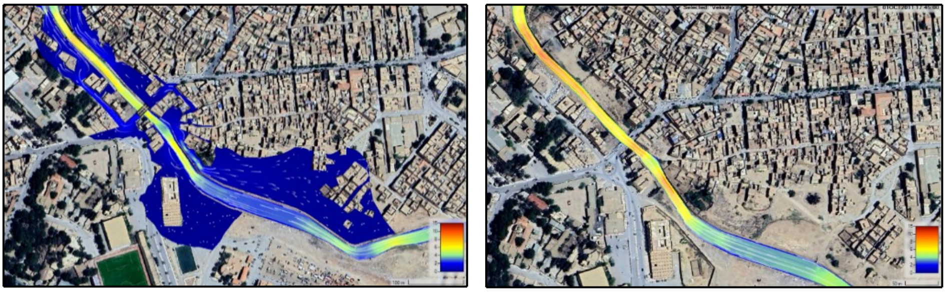

Figure 10: Flow behavior streamlines in city center - with bridges (left) and without bridges (right)

CONCLUSION

Although the flood risk in arid regions may appear low due to the scarcity of rainfall, its impact is substantial. This is because many dry areas or natural flow paths have vanished, creating a false sense of security. Additionally, these regions often lack sufficient data, and engineered flood control measures are frequently designed with significant uncertainties. As a result, the combination of these invisible risks and inadequate preparedness amplifies the risk of flooding in these regions. In this context, numerical modeling was employed to simulate the flooding of El-Bayadh city, with the aim of assessing the effectiveness of protection measures and improving understanding of the factors that exacerbated the recent devastating event. This case study reveals that the primary factor exacerbating flood risk in El-Bayadh is encroachment on the natural flow path. This encroachment restricts the channel's capacity, resulting in overflow and amplifying the risk. It is found that the actual capacity of the current channel is approximately 180 m3/s, significantly insufficient to handle a discharge similar to the 450m3/s experienced on October 1st, 2011. This underestimated capacity may primarily be attributed to the lack of appropriate data characterizing these regions, which creates a false sense of security, further encouraging encroachment within high-risk areas, ultimately amplifying the magnitude of the overall risk. Furthermore, the erratic flow of the Wadi channel, often remaining dry for extended periods, particularly in recent years, has enticed people to settle in flood-prone areas, mistakenly perceived as safe land. These actions, particularly during heavy rains or extreme events, pose significant risks and contribute to the heightened human and material losses as witnessed in the recent flooding of El-Bayadh. The findings also suggest that, without bridges, the channel capacity could likely handle events similar to the October 1st, 2011 flood. Yet, it remains uncertain whether the initial canal design would have been adequate for the such volume of floodwater. It's possible that bridges were constructed without sufficient hydraulic evaluations, diminishing the channel's water flow management capabilities. Furthermore, the addition of bridges to accommodate population growth might not have been accompanied by updates to the canal's overall hydraulic capacity. Despite valuable insights from past studies on El-Bayadh, the current capacity of the Deffa Wadi channel and its surrounding structures is demonstrably inadequate. This poses a significant risk of a repeat of the devastating October 1st, 2011 flood. To effectively tackle El-Bayadh's flooding and prevent future disasters, immediate intervention is crucial. This multi-pronged approach should encompass restoring encroached areas to unlock the natural flow capacity, developing programs to incentivize or assist residents in relocating from high-risk zones, and implementing and rigorously enforcing stricter regulations to prevent further encroachment on these vulnerable areas.

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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