Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28230

263 (2022) 197–203
July

Flood damage assessment of vulnerable area in Riyadh city, Saudi Arabia — case study: Al-Thumama Bridge

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Received 28 February 2022; Accepted 14 May 2022

ABSTRACT

Flood damage assessment is becoming now more important because of flooding disasters around the world. Severe rainstorms are common occurrences in some regions of Saudi Arabia that result in hazardous floods damaging the infrastructure and development plans. This study is applied in order to assess the flood hazards in the study area and to propose some countermeasures to reduce the flood damage. In recent years, Riyadh has experienced several flooding events that caused damages in and around the city in different locations due to the change in climate and land use. The paper presents a framework for a study of flood damage assessment of vulnerable area in Riyadh that was exposed to severe damages occurred by flash floods. As well as, conducting analyzes of morphology, metrology, hydrological and hydraulic analysis are included. Then, proposing a plan to mitigate the damages happened to the study area. The prediction of rainfall depths for 50 and 100-y were estimated using the frequency analysis to be 46.5.6 and 52.2 mm, respectively. The peak flow rates at the catchment outlet for 50- and 100-y return periods were estimated to be 256.0 and 291.0 m^3/s, respectively. The weighted Curve Number value of Wadi basin was estimated to be 81. In the hydraulic modelling, the Manning roughness coefficient was increased to 0.03 to dissipate the energy at the baffles and drops. The scour depths at the bridge piers were estimated assuming that the valley cross section does not tolerate the high water velocities. The study recommended taking into account the expected scour depth which obtained from the hydraulic modelling and the Wadi bed condition to guide the designer to use deep foundations at the piers of the bridge to overcome and alleviate from the flash flood impact.

Keywords: Flood damage; Mitigation; Curve number; Water flow

1. Introduction

Flood is a natural process that occurs when water inundates land that is ordinarily dry especially in arid and semi-arid regions and occurs when rainfall volume is not absorbed by ground soil due to the very low infiltration capacity which results in the huge amount of surface runoff [1,2]. The amount of this runoff depends on the nature of the catchment, the rainfall intensity, the soil moisture content and the drains. Areas that are prone to flooding include those that are located downstream of dams and low lying areas. The ability of flood water harvesting in one of the ungauged sites of Riyadh region was evaluated by [3]. They calculated high-frequency flood discharges and runoff volumes using various methods including Soil Conservation Service (SCS) Dimensionless Unit Hydrograph (DUH) method.

Flooding causes losses which include loss of life, soil erosion, damages of properties, and environmental damages. Flood waters are usually polluted with harmful bacteria resulting from sewage. This means that people affected by the floods are at greater risk of getting infected

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

diseases. Iloeje et al. [4] considered that flooding is a major environmental phenomenon creating severe impacts on the socio-economic and environmental aspects of human endeavour. Most regions around the world have experienced extreme climate change rainstorms in recent years [5–7]. Such incidents contribute to life, property and economic damage disasters. Saudi Arabia has suffered unprecedented events that caused serious damage in roads, railways, urban zones and farmland [8]. The combination from all theses factors climate change, and heavy rainfall, lack of drainage systems and unexpected urban expansion is the main cause of the flash flood hazards in Saudi Arabia.

Saudi Arabia is one of the countries that are prone to the risk of floods that cause different types of damages. The highest past flood events and their damages in different regions of Saudi Arabia were on the 24th of December 1985, heavy rains poured on north-western regions of Saudi Arabia, leading to what has been described as the worst flood in the area in 50 y. Estimates of damage were not recorded, except at least 32 people were killed from the flood. Heavy rains poured on western Saudi Arabia in January 1997, mainly affected Yanbu and peripheries of Jeddah. It was noticed that the rain lasted for 24 h where 10 people were killed and an area of over 130,000 km^2 of land was damaged. Also, in Asir, a province in the Southwest of Saudi Arabia, on Monday, 25th of March 1997, the area was exposed to heavy rains causing floods and resulted in 16 fatalities and an area about 100,000 km^2 of land was damaged. Recently, flash flooding in Saudi Arabia areas has been triggered by heavy rainfall as what happened in Jeddah city (years 2009, 2011, 2017 and 2018) and Al-Riyadh (2015 and 2018), as was mentioned in General Directorate of Civil Defense of Riyadh Region [9].

In the western part of the country, especially in Jeddah (November 2009 and January 2011), different areas have been affected [8,10]. In 2016 a heavy rain storm lasted for more than 12 h on AlDulm located in the south of Al-Kharj town, has resulted in the detention of many vehicles inside and causing damage to many properties. The damage extended to different districts of AlDulm.

Al Saud [11] utilized space techniques supported by GIS with a focus on IKONOS satellite images, which are characterized by high resolution in identifying terrain features. Thus, damaged areas and the mechanism of flooding process were recognized in the study area and this helps avoiding further urban expansion in areas under flood risk and will aid decision maker to put new strategies for hazard management.

Al-Momani and Shawagfah [12] highlighted the capability of GIS and satellite images for quantifying and mapping the flood characteristics in the city of Tabuk, Saudi Arabia. Various thematic maps including drainage, lineament, lithology, slope and land use have been generated using those techniques, which are efficient tools to define topography and morphological changes. Generated results and maps helped to analyze and manage flood hazards, and also to formulate remedial strategy such as evacuation, flood routing and provision of water retaining structures.

Rahman et al. [13] identified city areas and residents vulnerable to flash floods recognized that under the evident climatic warming, the Riyadh city has increased risk of exposure to frequent flash floods in the next 25 y. While the physical vulnerability of the city to flash flooding was assessed by simulating 6 h of intensive rainfall and measuring the depth of flood water, its social vulnerability was assessed by standardized ranking of census data on seven demographic, social, economic, and urban built-up environment variables.

Abo Salima et al. [14] have developed a systematic methodology for estimating flood hazard areas in Jeddah region using GIS. The flood hazard map from their study can be used to identify zones of the study area that are prone to high flooding risk and to design flood preventing structures and plan new land use for future developing areas.

Sharif et al. [15] examined flood hazards in a rapidly urbanizing catchment in Riyadh city, Saudi Arabia. They used remote sensing data and GIS techniques to prepare inputs for hydrologic and hydraulic models. The impact of urbanization on run-off volume and peak discharge resulting from different storms was investigated, with various urbanization scenarios simulated. The catchment response was found to be quite sensitive to an increase in the urbanized fraction. Flood hazard zones and affected streets were also identified through hydrologic/hydraulic model simulation.

2. Study area

Riyadh city is considered one of the cities are vulnerable to flood risk in Saudi Arabia due to urbanization and recent development as well as climate changes. Al-Thumama Bridge is one of the bridges located at the Wadi Banban pathway in Riyadh. The bridge has consisted of 13 openings with a total length of 195 m. Fig. 1 shows the catchment area and location of Al-Thumama Bridge. The flood damages at Al-Thumama Bridge were due to one of the heaviest storms that hit Riyadh city in November 2013 that caused many damages to people and properties. The storm in whole Riyadh caused an evacuation of people in danger and then sheltering them; two families were consisting of 23 people. And many 78 people were detainees rescued and the numbers of vehicles taken out were 74 cars. The total economic and life losses due to the 2013 storm in Riyadh are as follows: number of deaths 3 people, number of injuries 11 people, number of missing 2 people, with a total of 19 sites where tunnels or roads had an increase of the water level within the city.

3. Research methodology

The most important step involves defining the geomorphology of the study area by using Watershed Modeling System (WMS) software. These involve the main basin and sub-basins of all the catchment, drainage networks and the longest stream path in each sub-basin. The second-step relates to the flood assessment method formed using HEC-HMS and HEC-RAS software.

3.1. Meteorological analysis

Riyadh station (R001) was selected due to the long record, which it has about 30 y of data records where intensity duration frequence (IDF) curves can be constructed to include most of the storm events that occurred in the region. Hyfran-plus software was used to find the design rainfall rate of the catchment. The results obtained have shown that the Gumbel method is better to use than Log Person III. It was found that the value of maximum rainfall of 100 y return period is 52.2 mm, and the value of maximum rainfall of 50 y return period is 46.5 mm, and for 20 y is 38.9 mm. Fig. 2 shows one of the Hyfran-plus output for developing the rainfall depth, duration and frequency curves.

3.2. Determination of the drainage basin and the morphological data

Watershed Modeling System (WMS) was used to determine the drainage basin, boundaries of the drainage basin, the pathways of the channels and branches of Al-Thumama Bridge catchment area.

The DEM with resolution 90m × 90m from the Shuttle Radar Topography Mission (SRTM) topography is available from the United States Geologic Survey (USGS) was the main input to Watershed Modeling System (WMS) to determine the catchment boundary and the stream network.

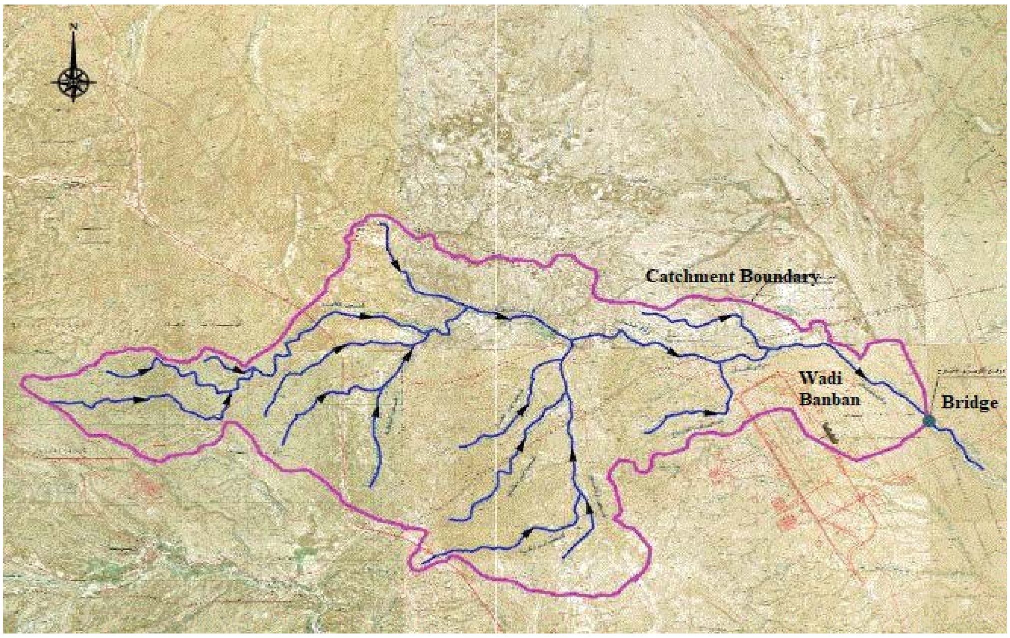

Fig. 1. The catchment area and location of Al-Thumama Bridge.

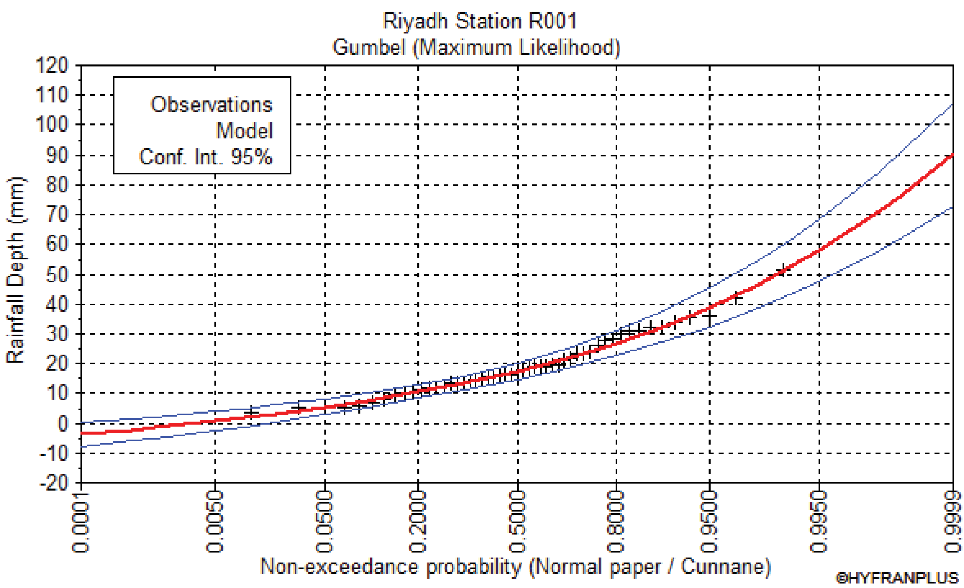

Fig. 2. Gumbel fit of maximum daily data of Riyadh station (R001).

The catchment area of Wadi calculated by WMS is equal to 381.0 km^2. The catchment boundary and the stream network are shown in Fig. 3.

3.3. Equivalent curve number (CN)

There are several types of land use inside the drainage basin as shown in Fig. 4. The curve number refers to functions of various factors which include hydrologic soil groups, cover type, treatment, hydrologic condition, soil moisture content, and impervious area in the catchment. Hence, theoretically, the curve number may range between 0 and 100 [16]. The weighted CN value of the basin was estimated to be 80.71 according to the land uses and the hydrological soil groups.

3.4. Hydrological analysis

Hydrological analysis is conducted to define the hydrological parameters for the main Wadis contributing with

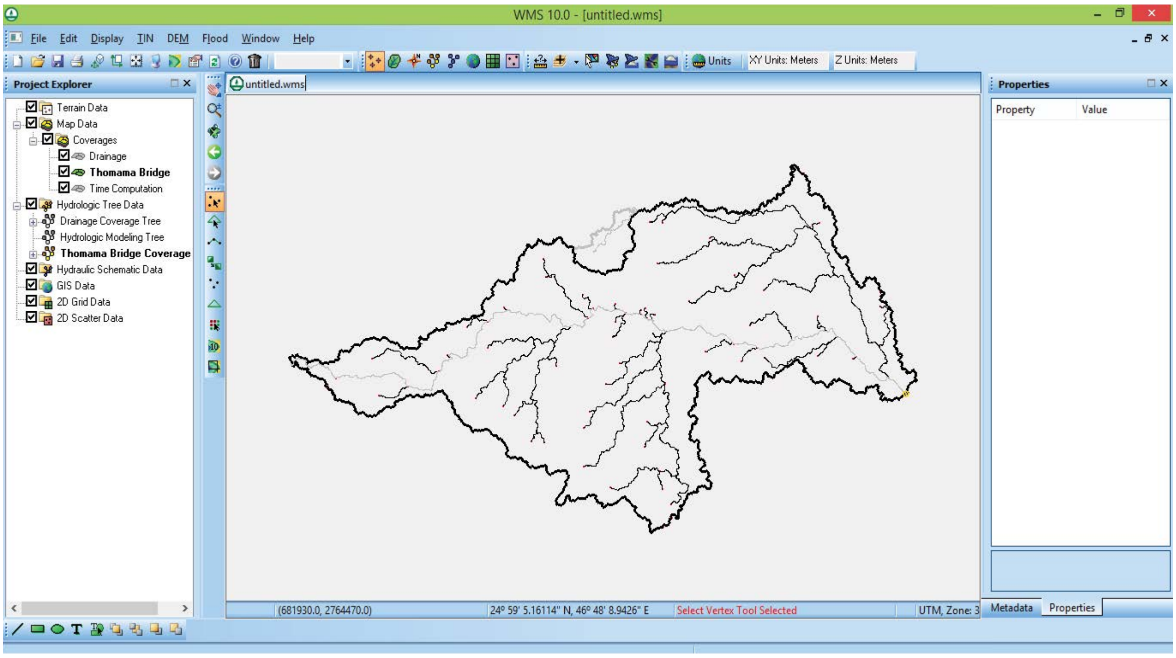

Fig. 3. The catchment boundary and the stream network.

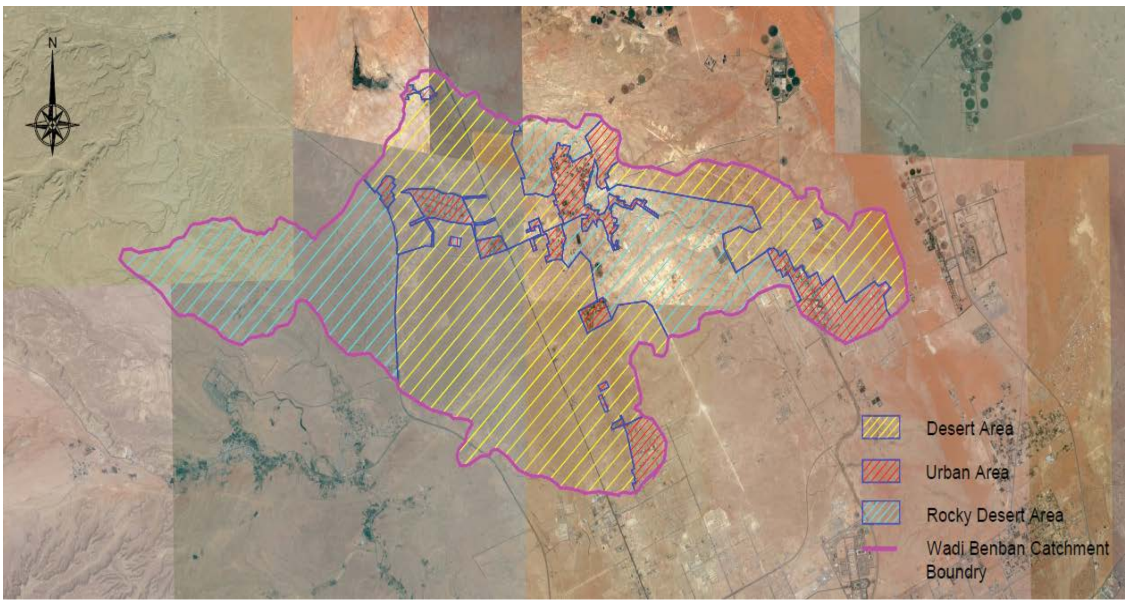

Fig. 4. Boundaries of the catchment and land use [17].

the study area such as time of concentration (t_c), Lag time (T_{lag}) as well as the peak discharges resulting from their catchment areas. This is done by the Hydrologic Modeling System (HEC-HMS) (the methodology of SCS-CN method). After adding the rainfall depths probabilities for 50 and 100 y return periods in the HEC-HMS model, the result findings were collected as outlet hydrographs. Additionally, for both return periods, the peak flows at the catchment outlet point 256.0 and 291.0 m^3/s were estimated for 50 and 100 y return period respectively. The basin lag time of the catchment was estimated to be 610.94 min.

3.5. Hydraulic analysis and HEC-RAS computation

The purpose of the hydraulic analysis is the determination of hydraulic characteristics such water depth, water velocity, the water levels in front of and behind the bridge, in addition to the dimensions of the water section at a specific location as well as the scour depth at the piers.

Definitions of reaches and geometry of floodplain and Manning roughness values are required by the Hydraulic model (HEC-RAS). WMS and HEC-HMS were used in the preparation of HEC-RAS input data in this study. The extractions of channel centerlines and the flood plains were made from the DEM.

4. Results and discussions

Hyfran plus prohram was used to perform the frequency analysis for the historical rainfall data to get the daily maximum rainfall depths for different frequencies. The prediction of rainfall depths for 50 and 100 y were estimated to be 46.5.6 and 52.2 mm, respectively. The Watershed Modeling System (WMS) and Arc-Hydro tools were used with the help of Digital Elevation Model (DEM) to define the main Wadi, its tributaries, drainage basin area and the morphological characteristics. The methodology of SCS-CN method was performed to estimate the peak flows at the catchment outlet point to be 256.0 and 291.0 m^3/s for 50 and 100 y return period respectively. The weighted Curve Number value of Wadi basin was estimated to be 81. Hydraulic modeling was done using the HEC-RAS program to determine the characteristics hydraulics for different sectors of water level and velocity, as well as determining the expected depth of scour around the bridge piers. In the hydraulic modelling, the Manning roughness coefficient was increased to 0.03 (Eartch channel-weedy) to dissipate the energy at the Baffles and drops. The scour was estimated assuming that the valley cross section does not tolerate the high water velocities. The model was undertaken with some details of networks of the reaches until the observed effect on the subsequent inundation maps was considered as shown in the program outputs. The depths conforming to the maximum discharge which HEC-HMS computed at the distinct cross-sections and accomplished interpolations along the reaches were computed by HEC-RAS. Fig. 5 shows longitudinal projection of water surface for the valley and also it can be noted the inundated areas estimates for different frequencies.

As noted before, the scour at bridge piers which happened for the old bridge was the main factor for the failure. So, it was recommended to check the safety of the proposed bridge against scouting. Scour depth was estimated using HEC-RAS, the results obtained show scour depths against the flood of 100 y equals to 5.7 m for peir (1) and 5.6 m for pier (2). Fig. 6 shows cross-section in the bridge after scour occurring. This means that all piers foundations for the proposed bridge should be deeper than estimated scour depths to ensure the bridge safety and its stability against the flow of 100 y frequency. On the other hand, the water velocity was estimated to be 6.3 m/s where it is somewhat high, so we may add more baffles to reach the allowable water velocities. Another alternative solution may be proposed

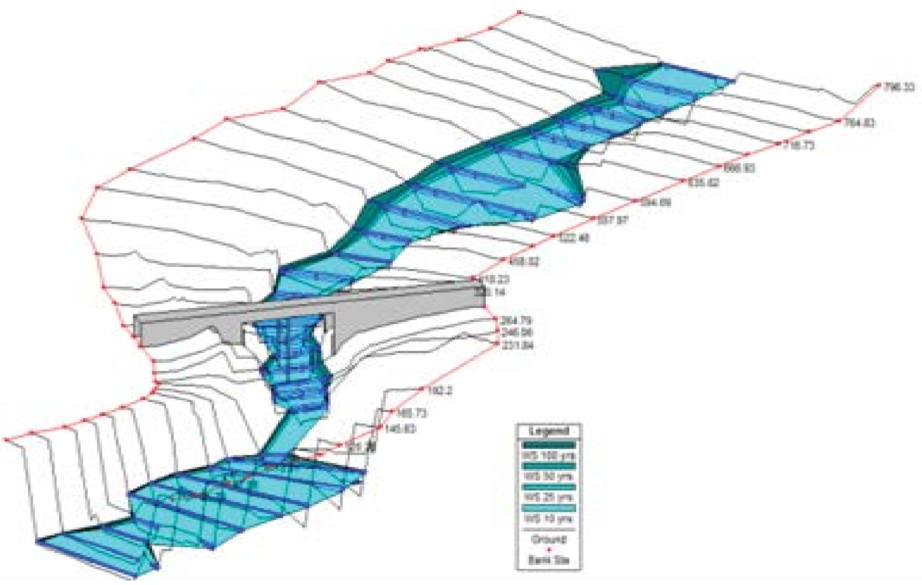

Fig. 5. Longitude projection of water surface for the Wadi.

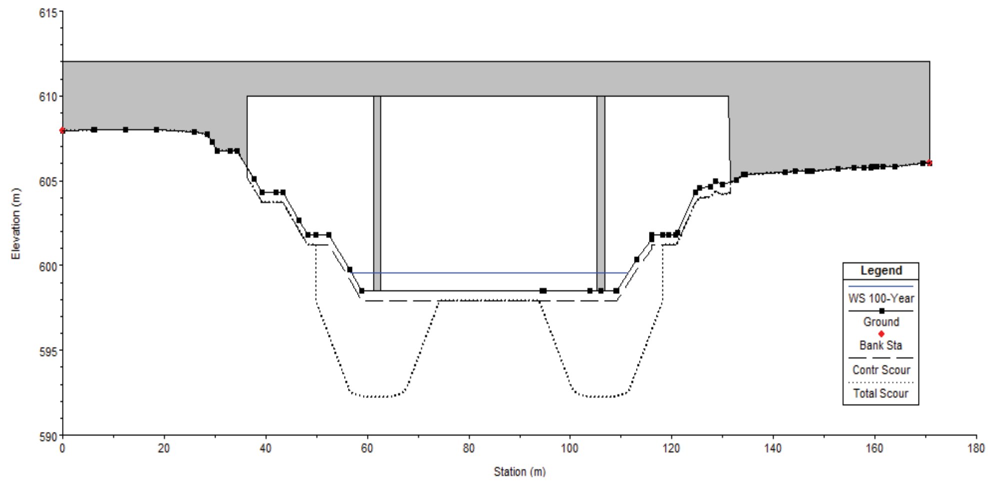

Fig. 6. Cross-section in the bridge after scour occurring.

by altering the cross section of the valley at the upstream and downstream of the bridge to make sure that there is no hydraulic interference between the water section and the pier locations, as well as avoiding the high water velocities.

Other proposed mitigation measure is protecting bridge from scouring impacts which may include strengthening and enforcement of Wadi bed around bridge piers and abutments by pouring of large aggregates and stones with bed soil and lateral sides.

It was shown from the results that the collapse of the bridge was due to deep scour at bridge piers below foundations as a result of high flow velocity and soil type of Wadi bed. For that reason, it was proposed to check the design of the proposed bridge against scour using 100 y flood frequency, as well as strengthening the Wadi bed.

5. Conclusions

This paper provided a basis for a flood-damage analysis of one of the vulnerable areas in Riyadh (Al-Thumama Bridge) which was subjected to severe flood-related damage. The current research demonstrated estimates of the expected flows beneath the bridge and suggests the appropriate hydraulic section and to investigates the resulted scour depths at the bridge piers due to the expected flows. This scour depth should be taken into account in bridge design to ensue not occurring any failure for the proposed bridge constructed across the Wadi. The methodology included the help of relevant programs (i.e., WMS, HEC-HMS and HEC-RAS). The study has shown the effect of flooding on the chosen site of the area involved in working simulations for the dimensions of potential flow of each frequency and the limits of growth and the extent of harm to humans and surrounding facilities, taking into account the urban development within the boundaries of the drainage basin. The value of the weighted curve number was estimated based on the urban development and land-use changes. The hydraulic modelling was done by HEC-RAS to determine the hydraulic characteristics for different sections to include the water levels, flow velocity and the expected scour depth at the bridge piers. Another parameter was considered in the hydraulic modelling which is the Manning roughness coefficient, which was increased to 0.03 to dissipate the energy at the Baffles and drops. The study has shown significant values of the scour depths at the bridge piers due to the high water velocities under the bridge which happened during the storm event. This problem may lead to the bridge collapse if those values of the scour depths did not take into account during the bridge design.

So the study recommended taking into account the expected scour depth which obtained from the hydraulic modelling which guides the designer to use deep foundations at the piers of the bridge. Also, it is recommended to use some accessories or devices in the stilling basin to dissipate the energy at the downstream of the valley. Also, it is recommended to strengthen the soil type of the bed to match it with the calibrated value of the roughness coefficient used in the modelling to reduce the flow velocity and hence dissipate the high kinetic energy which causing much scour.

Acknowledgments

The authors extend their sincere appreciations to the Ministry of Transportation, Riyadh, Saudi Arabia for their valuable information regarding to that study. Special thanks also to the reviewers for their suggestions and improvement of the manuscript.

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