Jurnal Kejuruteraan 36(1) 2024: 169-177
https://doi.org/10.17576/jkukm-2024-36(1)-16

Modelling of Riverine Flooding Using HEC-RAS-A Case Study of Badri Khawar River in KPK, Pakistan

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Received 3 January 2023, Received in revised form 14 June 2023
Accepted 14 July 2023, Available online 30 January 2024

ABSTRACT

Floods are one of the most occurring disasters in the world. Pakistan gets affected by flooding due to its diverse geography and has to lose several lives of people every year. The main objective of this study was to carry out modeling of riverine flooding using HEC-RAS program to estimate the safe channel capacity of the project reach and identify the vulnerable areas along the project reach for different flooding scenarios. A 9.21 Km long reach of Badri Khawar river, a right bank tributary of Indus River in KPK province has been taken as a case study. Based on the available data, one dimensional steady flow analysis in HEC-RAS has been carried out for different flooding scenarios. By analyzing the simulated results, the safe channel capacity of the study reach was found to be in the range of 125m^3/s to 100m^3/s from upstream to downstream. Based on the extent of flooding in different scenarios, vulnerable areas have been delineated on a flood map devised by the help of Google Earth. There is more inundation at the left overbank as compared to the right overbank. For the worst-case scenario, the maximum estimated flood extension on left bank side was about 425m while on the right bank side it was 204m. Based on the results of this research, it is suggested to enhance the existing flood protection measures along the project reach and improve the flood warning system and emergency evacuation mechanism in the vulnerable areas for long-term flood safety.

Keywords: Flood disaster; Badri River; Flood Modeling; riverine flooding; flood safety

INTRODUCTION

Floods are the overflow of water from the banks of rivers and inundate the dry land. Floods are the second highest most occurring disaster in the world after earthquake. Numerous people get affected by the floods in Pakistan every year. Several people have to migrate from their accommodations with their families and children. Flooding has always been a part of human history. Many ancient civilizations developed along waterways and rivers because people needed water for their fields. Main types of flood include: cat-III flood, coastal flood, urban flood, river flood and flash flood. Each type of flooding occurs due to its own specific reasons (Afzal and Ehsan, 2015; Natarajan and Nisha, 2020; Munoz et al. 2021; Sopery et al. 2022).

Floods in a river valley are generally prompted by heavy rainfall in uplands. The water flows from highlands through streams and tributaries falling into the river. This surplus of water in river results into inundation across river valleys. The flow patterns differ according to the geometry of the of river valley. In the case of high flooding in a river valley, the extent of flooding also changes with respect to the typical shape of the river valley. For different rivers, the response of the river valley to flood water would certainly be different (Ehsan et al. 2016).

Pakistan comes across flooding due to its diverse geography. Pakistan is situated among Northern upland engulfed with glaciers and South belt bordered with the Arabian Sea. Pakistan is shoved by the five substantial and sizeable rivers from North to South namely Jhelum, Chenab, Sutlej, Ravi and the mighty Indus. July to September is an explicit and well-marked Monsoon season in which the whole country embraces rainfall. Riverine flooding is habitual in low lying areas along the river during this time while flash flooding is also occurring in hilly and semi hilly areas. Intensive rainfall in the catchment areas of river augmented with the snowmelt flow outturns the floods in Pakistan (Khan 2013).

Pakistan as a developing country is unable to tackle the natural flood disasters. Therefore, it results in gigantic loss of resources, agriculture and most importantly human beings. The catastrophic aspect is that it will be supervened year after year until strong and effective flood preventive measures are not taken at government level (Khan 2013).

According to the official figures released by Federal Flood Commission (FFC), Ministry of Water and Resources, Pakistan, loss of life and financial loss caused by the major floods events in the history of Pakistan are shown in the Figure 1 and Figure 2 respectively.

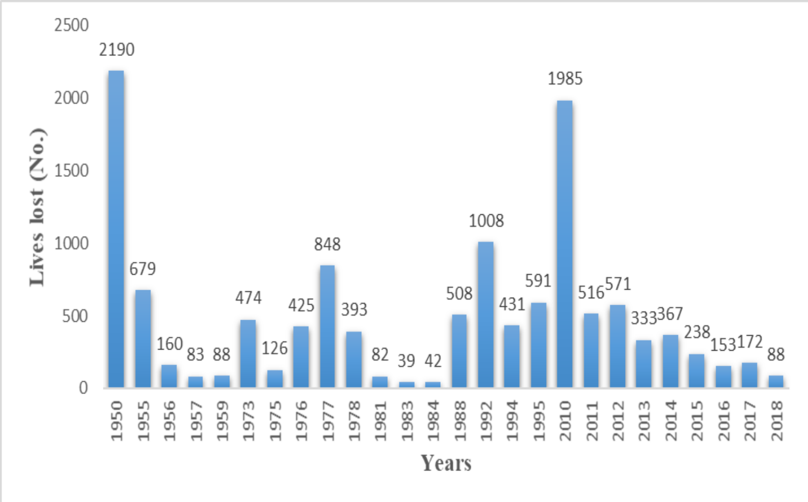

FIGURE 1. Lives lost due to floods in different years
Source: Annual Flood Report (2018c)

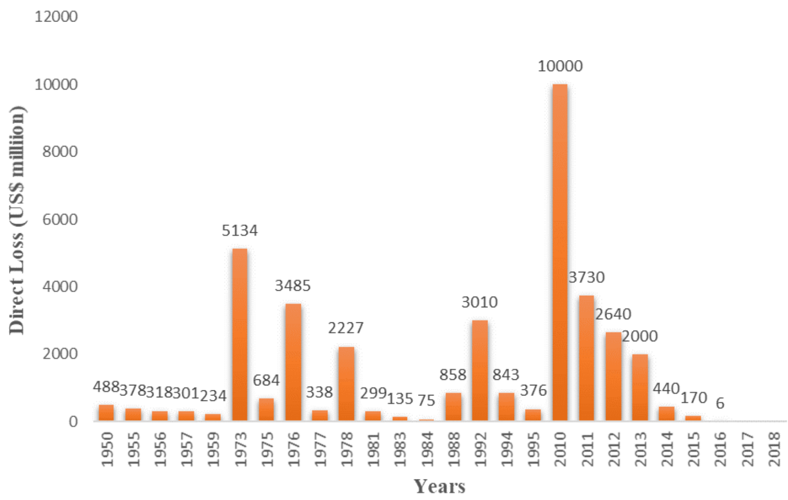

FIGURE 2. Financial loss due to floods in different years
Source: Annual Flood Report (2018c)

In Pakistan, flood management is a substantial challenge and requires experience and great integration on side of planners. The nature of floods and its challenges differs in each province of the country. These variations depend upon varying physiographic, demographic, climatic and socio-economic conditions. In Punjab, marginal bunds have been constructed to safeguard the irrigation structures, agricultural land, villages and some towns.

As Sindh province is located at the tail end, it has to face adversity if the proper flood protection measures are not adopted in upper Sindh. In Khyber Pakhtunkhwa (KPK), floods occur due to flash flood flows in the secondary rivers (Swat, Panjkora, Kabul, etc.) and hill torrents flow generating nullahs having steep bed slopes, which increase flood velocity and severely erode the banks of the river. Similar goes with Baluchistan physiography.

Gilgit-Baltistan, FATA and AJK also have the same climatic and physiographic characteristics to Baluchistan and Khyber Pakhtunkhwa (KPK). The main existing Flood protection measures include flood peak regulations by reservoirs. There are three major reservoirs in Pakistan, Mangla on Jhelum and Tarbela, Chashma on the mighty Indus (Annual Flood Report, 2018a; Annual Flood Report 2018b; Annual Flood Report 2018c).

Flood prediction models are of significant importance for hazard assessment and extreme event management. Accurate and durable predictions of floods contribute in policy suggestion, analysis and water resources management strategies. To alleviate damage, the significance of advance system for short term as well as long term prediction for hydrological events is increased. The prediction of flood lead time and occurrence location is fundamentally complex due to the dynamic nature of climate condition. Thus flood modeling is fundamentally data specific and includes various assumptions. (Solomatine and Ostfeld, 2008; Mosavi et al. 2018)

There are two types of hydraulic modeling used in the prediction of floods. Each one of them has its own limitations. The major types of hydraulic modeling approaches are: (Solomatine and Ostfeld 2008; Maniyar and Bhatt 2015; Mosavi et al. 2018).

1. Physically based models
2. Empirical or Data driven models

Physical based models were long used to predict different hydraulic events. Data-driven methods of prediction assimilate the measured climate indices and hydro-meteorological parameters to provide better insight. In recent time, ready to use programs have been introduced. (Solomatine and Ostfeld, 2008; Mosavi et al. 2018)

These are many computer programs which asses water surface profiles of the flow and changes caused by various hydraulic structures. They are also used in the designing of hydraulic structures to determine the levels of floods. Programs like MIKE-11 (owned by DHI) are not free for modelers, while HEC-RAS is owned by US Military and it is open source software that works properly without any subscription. In this study, HEC-RAS has been used for one dimensional Flood modeling. HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system of HEC-RAS includes a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities (HEC-RAS, 2021).

In this research, a reach length of 9.21 Km of Badri Khawar river in KPK province has been considered as a case study for steady flow analysis by HEC-RAS. Badri Khawar river is the right bank tributary of the mighty Indus river and outfalls in the downstream of Tarbela Dam near Harian just before Kabul river joining the Indus. Major portion of floods in the KPK flow through the streams having steep bed slopes. These streams have high velocity in floods which erode the banks. Badri Khawar river starts from upland of Buner District. The catchment area of whole Badri river is about 475 km^2 consisting 241 km^2 in the hilly terrain while remaining catchment area is relatively in plan terrain with agriculture fields. Badri river flows through the two major districts; Buner and Swabi District. The climate of these districts is generally warm and humid. This region lies in sub-tropical zone having average precipitation of about 639mm. Figure 3 shows the overview map of Badri river catchment (Badri River Report 2021).

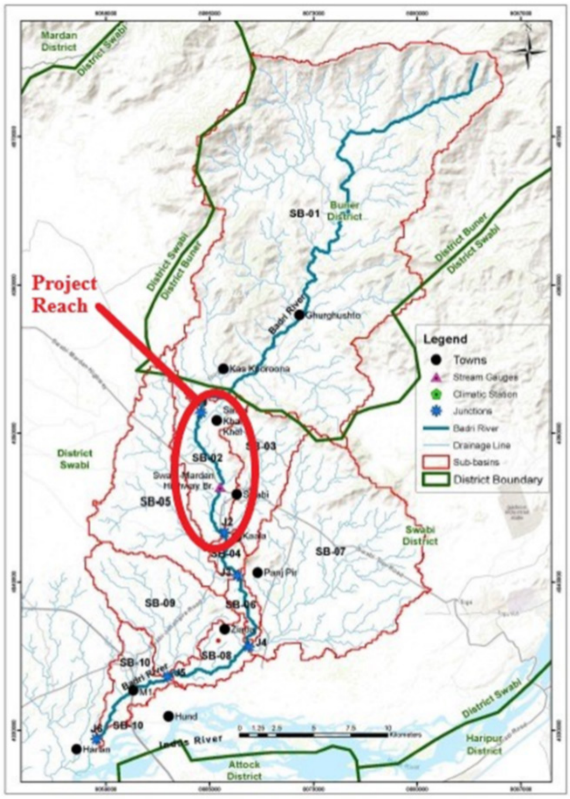

FIGURE 3. Overview Map of Badri River Catchment

LITERATURE REVIEW

In the past, many studies on flood modeling have been carried out using HEC-RAS. Some of the recent studies are mentioned below.

Ogras and Onen (2020) conducted flood analysis on Tigris River, Turkey using HEC-RAS. In this study, the floodplain analysis was handled between Diyarbakır-Silvan

Highway and historical Ten-Eyed Bridge.

Pathan and Agnihotri (2020) studied to demonstrate the geospatial analyzing capabilities of HEC-RAS. Arseni et al. (2020) carried out a study on Siret River, Romania for designing risk and hazard maps for floods, which could be further applied to other rivers. Naeem, et al. (2021) conducted a study on Tori Levee Breach of the Indus River Basin, Pakistan to assess the Flood Hazard by coupling a HEC-RAS 2D hydraulic model with remote sensing and Geographic Information System techniques.

Yalcin (2020) assesses the effects of topography and land cover data resolutions on the estimates of food extent, inundation depths, flow velocities, and arrival times of a two dimensional (2D) hydrodynamic HEC-RAS model under differently sized mesh structures, with the example of the urban floodplain of Kilicozu Creek (Kirsehir, Turkey). Chen et al. (2020) studied the Floodplain response to varied flows in a Large Coastal Plain River on Apalachicola River, Florida by comparing a relative elevation model (REM) and HEC-RAS 1D-model. Prastica (2021) performed 1D modeling in HEC-RAS and the vulnerability level assessment of Belik River sub- watershed, Indonesia. Husain et al. (2018) developed simulation of floods in Delhi Segment of River Yamuna using HEC-RAS.

The main aim of this study was to carry out modeling of riverine flooding using HEC-RAS for following purposes.

1. To check the safe channel capacity of the project reach.
2. To estimate flood extension along the project reach.
3. To delineate the vulnerable areas along the project reach.

DATA COLLECTION

Data collection is the first and hard step for a modeler. The concerned authorities were approached for data collection. The input data required for modeling in HEC-RAS was collected from the Water Resources Division of NESPAK, Lahore. Further, in subsequent meetings useful information about the project area was also gathered through personal communication with the relevant engineers. The collected data mainly comprises the following:

1. Geometric Data in the form of CAD File
2. Peak Discharge for various return periods

EXTRACTION OF CROSS-SECTIONAL DATA

The surveyed cross-sectional data was received in the form of CAD File. Total 18 cross-sections of the project reach were available for the length of 9.21Km.

Three dimensional distances were taken from CAD file. 3D- Polyline had been drawn from each station point and extracted the three-dimensional coordinates from this file. The process of joining the points of cross-sections was done by 3D-POLY command in CAD. These points were then copied to an excel sheet. After filtering the supplementary information, three columns of X, Y and Z coordinates on each surveyor point were developed.

In order to get the Station data, the distance between two consecutive surveyor points was required. That distance was calculated by using the distance equation between two points.

$$\text{Distance between two points (Station)} = \sqrt{(Y_2 - Y_1)^2 + (X_2 - X_1)^2} \qquad (1)$$

Where,
X_1 = x-coordinate of 1st point
X_2 = x-coordinate of 2nd point
Y_1 = y-coordinate of 1st point
Y_2 = y-coordinate of 2nd point

The Z coordinate extracted from the CAD file against each surveyor point has been used as elevation data. Each cross-section is separately extracted from the CAD and then modified it in the form of Elevation and Station.

CHAINAGE AND RIVER STATION

The actual station has been calculated by using the same approach that has been used while calculating the station data in the previous section. A 3D-polyline has been drawn in CAD by joining the points of River Bed (RB) in the direction of river. The lowest River Bed (RB) point has been selected for each cross-section to join by the polyline. X, Y and Z coordinates against each surveyor point were generated in CAD. These coordinates were then copied to excel and distance between the two consecutive points has been calculated. Distance formula i.e. Eq. (1) has been used again to calculate the distance between two points. That distances are the actual River Stations. The chainage has been calculated by the addition of all River Stations. The calculated reach length is 9.21 Km.

STEADY FLOW ANALYSIS IN HEC-RAS

For steady flow analysis in HEC-RAS, water surface profiles are computed from one cross section to the next by solving the Energy equation with an iterative procedure called the standard step method. The energy equation is mentioned as Equation (2): (HEC-RAS Reference Manual, 2021).

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e \qquad (2)$$

Where,
Z_1, Z_2 = elevation of main channel inverts
Y_1, Y_2 = depth of water at cross-sections
V_1, V_2 = average velocities (total discharge/total flow area)
a_1, a_2 = velocity weighting co-efficients
g = gravitational acceleration
h_e = energy head loss

FLOOD MODELING IN HEC-RAS

MODEL SETUP

The project reach was defined in HEC-RAS by inserting the extracted river cross-sections through the geometric data editor. The schematic layout of defined cross-sections is shown in Figure 4. The flow data was inputted in steady flow editor for different scenarios. The peak flow values were taken as upstream boundary condition for different flow scenarios. Further as per available data, the option of normal slope was used for defining the downstream boundary condition in all simulations.

As the reliable flow data at different river locations was not available for the past floods, so precise calibration was not possible. But in order to adjust the model to stable flow conditions, several steady flow pre-runs were made for overcoming the possible numerical instabilities in the model and finally an average value of 0.035 for Manning's coefficient was adopted at all river locations.

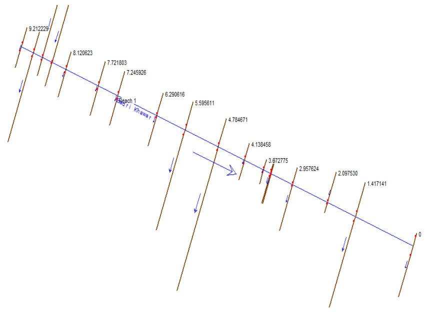

FIGURE 4. Schematic diagram of the reach in HEC-RAS

SAFE CHANNEL CAPACITY

Safe discharge capacity of a river cross-section is related to its size and shape and it shows the ability of a cross-section to carry a specific amount of discharge without overbank flooding (Ehsan, 2009). For this study, the safe discharge capacity has been estimated at each river cross-section by running several steady flow simulations and analyzing the change in water levels at downstream cross-sections with respect to the location of flood plains. The estimated safe channel capacity varies from 125m^3/s to 100 m^3/s. This is due to the change in the bank full area of respective cross-sections with respect to the change in their overall shape and hydraulic conditions. Figure 5 shows the safe channel capacity throughout the project reach.

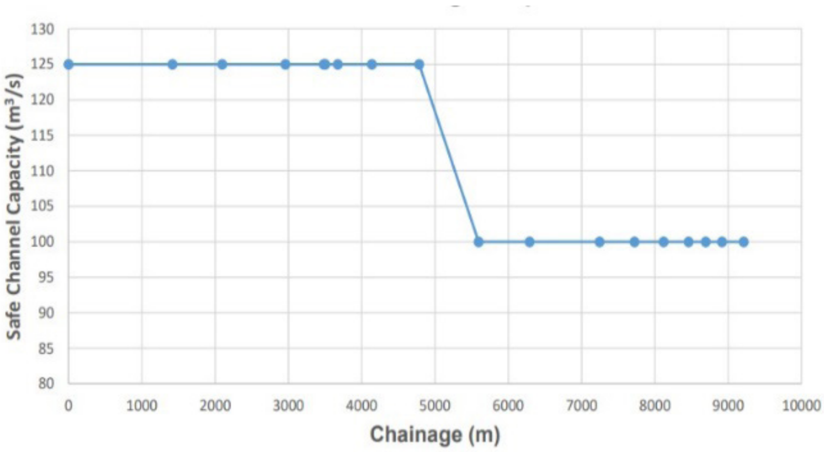

FIGURE 5. Safe channel capacity of the project reach

The variation of safe water level from upstream to downstream throughout the project reach is shown in the Figure 6.

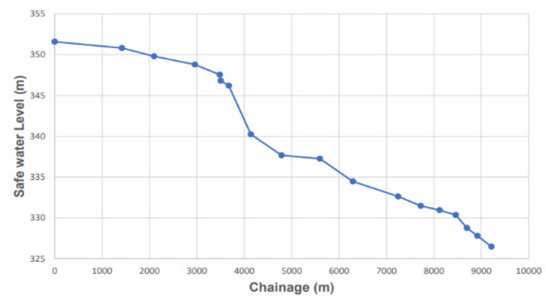

FIGURE 6. Variation of safe Water Level throughout the reach

CONSIDERED DIFFERENT SCENARIOS

Different flooding scenarios based on the estimated peak discharges against certain return periods (Table 1) have been considered for flood routing through the project reach in HEC-RAS.

TABLE 1. Peak Discharge for Different return periods at top of the Project reach (Badri River Report, 2021)

Return Period	Peak Discharge (m^3/s)
25 Years	667
50 Years	780
100 Years	897

Figure.7 clearly represents the significant increase in water level for all flooding scenarios in comparison to the safe water level. The red circle in Figure.7 shows the significant change in water level at the Chainage of 5.59 Km for 25 years return period discharge which is possibly due to the variation in the geometric shape of the respective cross-section.

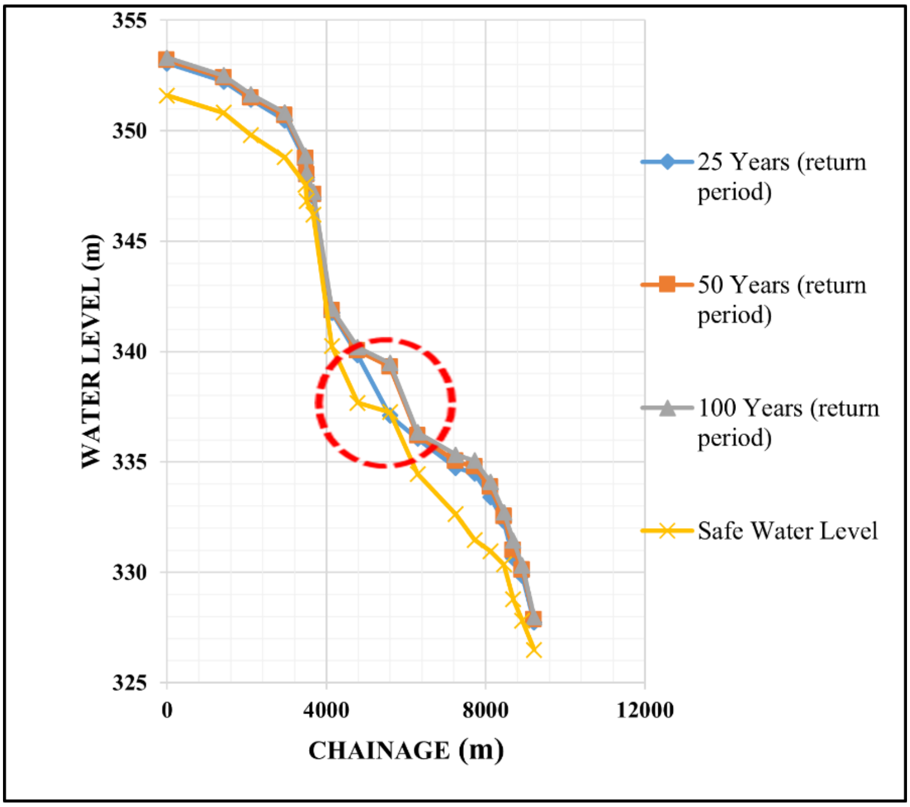

FIGURE 7. Comparison of Computed Water Levels

EXTENT OF FLOODING ALONG THE RIVER BANKS

In order to estimate the extension of flooding along the banks for different flooding scenarios, the simulated results have been analyzed at each cross-section. In all cases, the results showed more inundation along the left overbank as compared to that along the right overbank. This happened due to the shape of the river reach which had a high ground at right overbank as compared to the left overbank. Figure 8 shows the estimated flood extension along the both river banks for different flooding scenarios. The maximum flood extension along the left overbank was found to be 421.53m at the Chainage 7722m whereas the maximum estimated flood extension along the right overbank was 197.65m at the Chainage 6291m for the Peak discharge of 25 years return period (667m³/s).

The maximum flood extension along the left overbank was found to be 423.55m at the Chainage 7722m whereas the maximum estimated flood extension along the right overbank was 201.01m at the Chainage

6291m for the Peak discharge of 50 years return period (780m³/s).

The maximum flood extension along the left overbank was found to be 425.44m at the Chainage 7722m whereas the maximum estimated flood extension along the right overbank was 204.03m at the Chainage 6291m for the Peak discharge of 100 years return period (897m³/s).

The extension of overbank flooding poses severe risks to people and property located in the close vicinity of the river. The estimates of flood extension for different flooding scenarios are very useful for flood safety management along the river banks through strengthening of existing flood protection measures. These measures include enhancement in the existing bunds/levees along the river banks, flood awareness among the people at risk and improvement in flood warning mechanism and emergency evacuation techniques to reduce the possible losses.

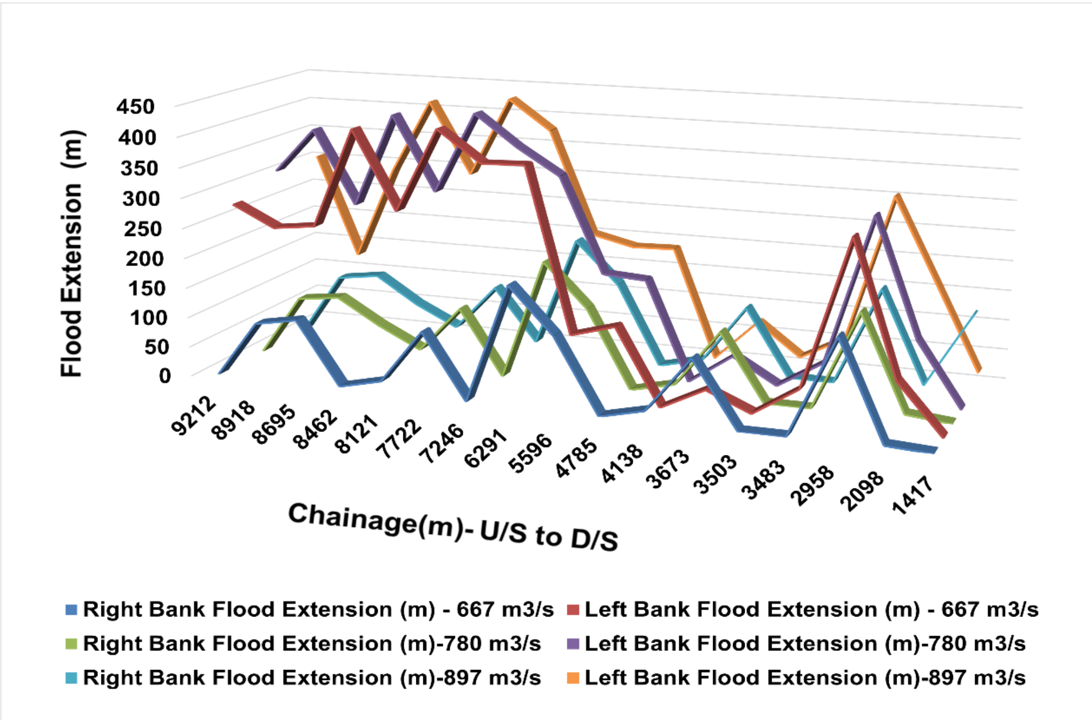

FIGURE 8. Estimated Flood Extension along the banks for different Flooding Scenarios

DELINEATION OF VULNERABLE AREAS

Based on estimated flood extension in different scenarios, the vulnerable areas along the river banks have been delineated which include mainly: Saleem Khan Village, portion of Saleem Khan Road, Agricultural Lands, Maneri Bara, Mami Khel, portion of Swabi District, portion of Mardan Swabi highway and Naro Banda. By observing the inundation in HEC-RAS and viewing the Google Earth view, it can be concluded that there is mostly hilly terrain at the right bank. A flood inundation map has been devised by the help of Google Earth (Fig. 9), which clearly depicts the flood extension in the considered flooding scenarios and also highlights the vulnerable areas along the project reach.Therefore, the right bank side is less inundated as compared to the left bank side.

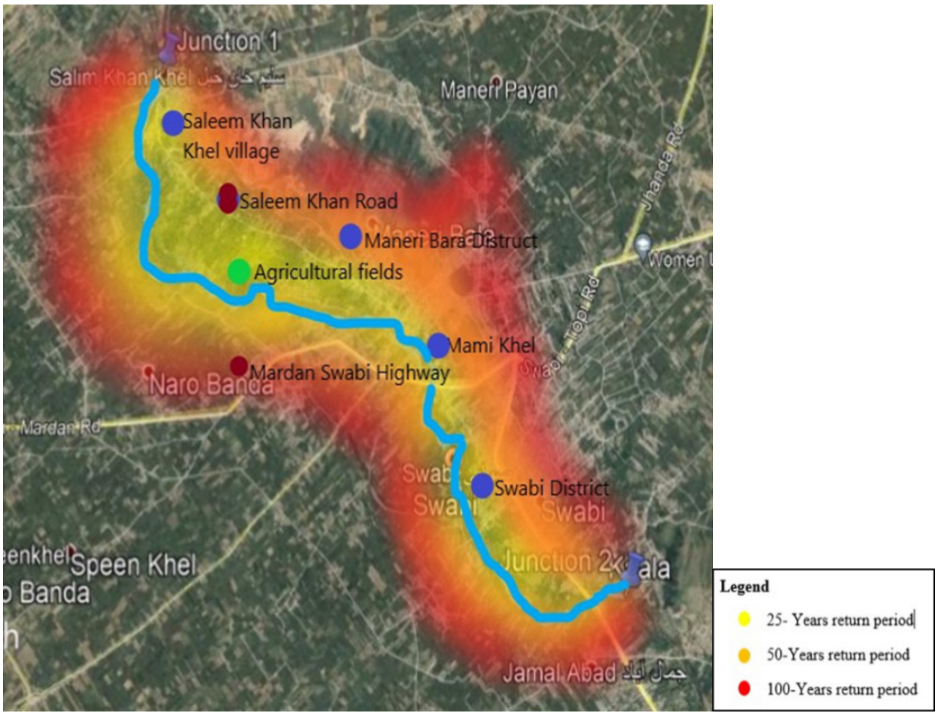

FIGURE 9. Delineation of Vulnerable Areas along the Project Reach

CONCLUSIONS & RECOMMENDATIONS

The estimated safe channel capacity of the project reach varies from 125m^3/s to 100m^3/s from upstream to downstream. The shape and geometry of the Badri Khawar river changes throughout the reach length, therefore, the flood inundation also varies along the river. By analyzing the simulated results of different flooding scenarios, the extension of flooding along the river banks has been estimated. In all scenarios, the results showed more inundation along the left overbank as compared to that along the right overbank. This happened due to the shape of the river reach which had a hilly terrain at right overbank as compared to the left overbank.

Based on the estimated extent of flooding, the vulnerable areas along the banks have been delineated with the help of Google Earth for the considered scenarios. For the worst case of peak discharge of 100 years return period (897m^3/s), the areas including Saleem Khan Village, portion of Saleem Khan Road, Agricultural Lands, Maneri Bara, Mami Khel, portion of Swabi District, portion of Mardan Swabi highway

and Naro Banda have been found vulnerable. These regions are partially inundated with the peak discharges of 50 years (780m^3/s) and 25 years return period (667m^3/s).

It is suggested to improve the existing flood protection measures along the project reach and also introduce new useful measure to minimize the possible damages caused by high floods. The related authorities should also start extensive flood awareness campaigns in the vulnerable areas and also improve the flood warning system as well as the emergency evacuation mechanism for the long-term safety of the vulnerable population.

More gauges should be installed at proper locations along the project reach as well as the whole Badri river to get more reliable data for detailed flood safety assessment.

The relevant authorities should also restrict the encroachments in the floodplains to avoid possible damages in case of extreme flooding in future.

ACKNOWLEDGEMENT

The authors would like to extend their gratitude towards the officials of Water Resources Division, NESPAK, Lahore for provision of related data/information required for the conduction of this study.

DECLARATION OF COMPETING INTEREST

None

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