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Flood modeling of Naray-Khwar using HEC-RAS

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Abstract

Flood Hazard Assessment of a river helps in predicting their behavior under different conditions. In this study, HEC-RAS model was used to simulate the steady flow water surface profile of Naray-Khwar, one of the largest water conveyance Khwar running through Peshawar carrying sewage affected significantly by urban interference. The methodology involved collection of geometry and flow data to perform various hydraulic calculations. For proper analysis, Naray-Khwar is divided into three channels with one junction under Nasir Bagh Bridge. Naray-Khwar Upper and Regi-Khwar Upper flow on the upstream while Naray-Khwar lower flows downstream of the junction. Horizontal distances along the corresponding elevations of 16 stations were measured using a total station. Due to the non-availability of measuring gauges, flow data was determined using rainfall data of Peshawar gauging station and was then converted into run-off using WinTR20 software. Frequency analysis was then carried out to calculate 2, 5, 10, 25, 50 and 100 years flood. The analysis showed that while most of the reaches at upstream of Nasir-Bagh Bridge are safe, it is the downstream side where the banks are over-topped by a very large margin.

Keywords: HEC-RAS, River Analysis, Hydraulic Modeling, Total Station.

1. Introduction

With the influx of Afghan refugees since 1979, population pressure on Peshawar has increased manifold as compared to other major cities. The housing needs and availability of cheap labor force resulted in a booming construction industry in Peshawar which led to the use of every available land in surroundings of Naray-Khwar for construction purposes. Initially, the sewerage network of Hayatabad was designed to carry 52.6 (L/s) of waste water from the first five phases up to the waste treatment plant. However, development along with population growth at a rapid rate resulted in an increased waste disposal which caused overloading of the sewage treatment plant. The upgraded sewerage system (0.5m - 2.5m) discharges a large amount of sewerage into the river, which is further enlarged by runoff from surrounding area including Tajabad town, Kacha-Garhai, Police Colony, University of Peshawar and surrounding localities. Furthermore, during the rainfall of 2008, 2010 and 2013, large amount of runoff coming from the upstream areas caused flooding of Naray-Khwar damaging public property, livestock, and other infrastructure.

River modeling using software is a recent practice but understanding the phenomena of River Mechanics is an old practice. There are a number of approaches described in conventional hydrological literature that are used to perform flow routing but hydrological routing models are used more often (Arora et al., 2001). (Singh, 1988) stated that Hydrological models are considered as spatially lumped form of the continuity equation. These are called water balance models. While HEC-RAS is an integrated software which is designed for performing one and two dimensional water surface calculations for natural as well as artificial channels. It can generate range of hydrologic responses for a river system by entering only its geometry and flow data (Burnner and CEIWR-HEC, 2010). Complex hydraulic models such as HEC-RAS, MIKE-11 rely on many high resolution morphological parameters (cross sections). These morphological parameters are often unknown at larger scales (Saleh et al., 2012). Although in developed countries, there is dense network of gauges for stage data collection but in non-industrialized nations this density is generally much lesser (Alsdorf et al., 2007). (Siddique-E-Akbor et al., 2011) stated the alternate solutions to overcome this deficiency which include satellite-based surface water estimation and development of hydrodynamic–hydrologic models.

Hydraulic models are developed using river geometry and the flow data. The flow is sometime obtained from flow gauges if available but if not, then rainfall runoff models will be developed using the available rainfall data as discussed in the following section.

Provision of general Monte Carlo approach to derive flood frequency for ungauged basins in Italy was attempted (Bonaccorso et al., 2017). One of these techniques was development of synthetic runoff hydrographs. Results reveal that this approach can be effectively applied to ungauged basins.

The rate-based runoff coefficient C of rational formula for 36 less developed watersheds of Texas was determined (Dhakal et al., 2013). For this purpose, peak flood generated by rainfall intensity corresponding to 2, 5, 10, 25, 50 and 100 years return period was used. It was concluded that C (T) values corresponding to T=10 years are more applicable to undeveloped watersheds. Study also reveal that the values obtained in this study are exceeding the values available in literature.

Rate-based runoff coefficients as a function of the return period, CðTÞ, were determined for 36 undeveloped water- sheds in Texas using peak discharge frequency from previously published regional regression equations and rainfall intensity frequency for return periods Tof 2, 5, 10, 25, 50, and 100 years. The CðTÞvalues and return period adjustments CðTÞ=CðT¼10 yearÞdetermined in this study are most applicable to undeveloped watersheds. The return period adjustments determined for the Texas watersheds in this study and those extracted from prior studies of non-Texas data exceed values from well-known literature such as design manuals and textbooks. Most importantly, the return period adjustments exceed values currently recognized in Texas Department of Transportation design guidance when T>10 years.

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A new technique of flood frequency analysis for the simulated annual peak flows (FASAP) was proposed by (Ahn, et al; 2014). In this method rainfall events with a time step order of five minutes were selected. Additionally, the new proposed method was verified by comparing its results with the conventional method in a real urban watershed and was found satisfactory.

The hydraulic and hydrological models are mostly applied for simulating flood runoff in the low-lying flood-prone areas, to determine the probability of the occurrence of the flood event, its magnitude, location and depth of the inundation in order to provide flood risk assessment information for flood management (Booij, 2005). This can be done through HEC-RAS using hydraulic data (River morphology and bed Roughness coefficients), topographic data (longitudinal profiles, river cross section and flood plain) and hydrological data (flood inflow hydrograph and discharge stage curve) required for flood modelling (Bemani et Al., 2012). Recently, HEC-GeoRAS tool is used for Floodplain zoning simulation and act as a bridge between GIS and hydraulic model developed in HEC-RAS software. Standard numerical methods (energy equation) are incorporated to calculate the surface flood level between the two sections needed for simulation. HEC-RAS also help in predicting the expected flood and its level early, thus maximizing public safety and minimizing property and other damage. This allows the fruitful venture of money and effort in the management of flooding (Burby, 2001). Other applications of HEC –RAS include (Knebla et al., 2005; Prata et al., 2011; Sunil et al., 2014; Yongping et al., 2011; Adewale et al., 2010). Keeping in view the application capability of HEC-RAS and the benefits of predicting the floods early, this study was conducted to determine the water surface elevation for floods of different return period estimated from Rainfall data collected from different sources. Therefore, the main objective of this study is to identify sections on the course of Naray-Khwar (Fig. 1) that are vulnerable to 100 years flood and compare it with floods corresponding to other return period flood. Since complex additional information is not available, the use of HEC-RAS was deemed particularly suitable to model steady flow water surface profiles of the river under study.

2. Study area

Naray-Khwar is an important part of the sewage and storm water collection system running through Hayatabad and the surrounding areas. Hayatabad, a modern township located on the south-western outskirts of Peshawar metropolis, is highly urbanized and has been institutionalized for the establishment of residential, industrial, educational and recreational facilities by Peshawar Development Authority (PDA). The township is spread over an area of 13.35km^2 comprising seven phases. The first and the last phases are of equal size, spreading over 1.57km^2 each, while the rest of the phases are smaller or larger than this size. Phase 5 is reserved for offices and housing colonies for various Government and non-government organizations.

The study focused on two Khwar, named Naray-Khwar and Regi-Khwar. Naray Khwar is further divided into upper and Lower Naray Khwar with reference to its junction with Regi Khwar under Nasir Bagh Road. Modeled portion of Naray-Khwar Upper is 2.58 kilometers long, Regi-Khwar Upper 1.01 kilometers long and Naray-Khwar lower is 1.58 kilometers in length. The HEC-RAS model is applied for the reach starting from Ring Road Bridge to the Professors Colony with junction under Nasir-Bagh Bridge. The channels are named on the basis of their position relative to the junction. Naray-Khwar Upper and Regi-Khwar Upper flow upstream of the junction and collect sewage from watershed-1 and watershed-2 respectively. First watershed starts from Bara hills and ends at the junction having catchment area of 178.5 km^2. Watershed_2 also ends at the junction having an area of 58.2 km^2.

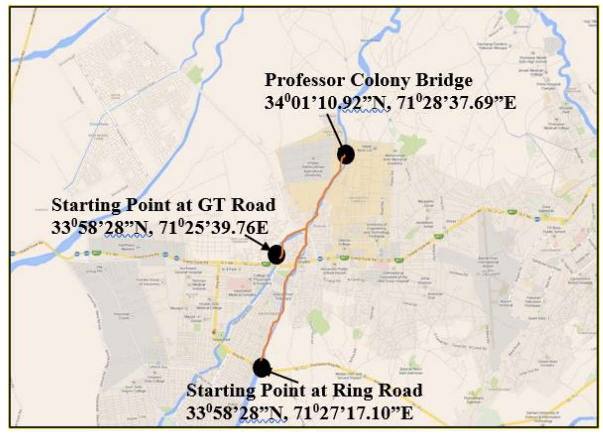


Fig. 1. Map of the study area.

The junction acts as an outlet for both these watersheds. Naray-Khwar Lower flows downstream of the junction.

Watershed_3 starts from the junction and ends at the bridge near the Professors Colony and had an area of 18.4 km^2.

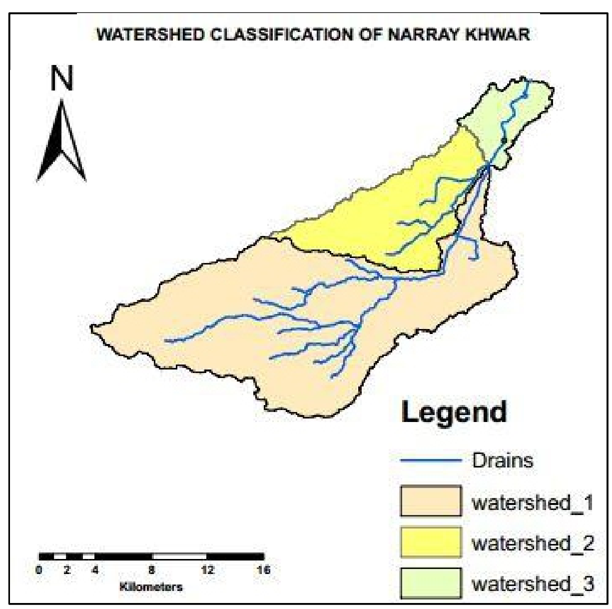


Fig. 2. Watershed boundary of Naray-Khwar.

3. Data collection

3.1. Geometry data

The channel geometry needed to route Naray-Khwar was collected by conducting survey at sixteen stations using total station starting from Peshawar Ring Road. The length between each consecutive cross- section and their numbering according to the order adopted for HEC-RAS application is given in Table-1 as follows. It is to mention that HEC-RAS named the most downstream X-section as 1 and upstream X-section as 13. Manning's roughness coefficients are selected from a pre-determined table.

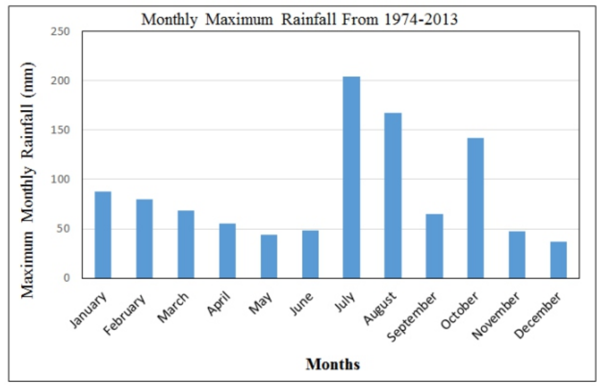
Table 1. Cross sections with name and distances between each consecutive cross section.

S.No	River	Reach	Distance between X-sec	Gap between X-section Center Line (m)
1	Naray Khwar	Upper	13 &12	972.7
2		Upper	12 &11	773.5
3		Upper	11 &10	95.8
4		Upper	10 &09	119.4
5		Upper	09 &08	422.0
6		Upper	08 &07	198.3
7	Naray Khwar	Lower	07 &06	139.0
8		Lower	06 &05	244.8
9		Lower	05 &04	186.4
10		Lower	04 &03	166.1
11		Lower	03 &02	142.3
12		Lower	02 &01	703.6
13		Lower	01 &00	0.0
14	Regi Khwar	Upper	10 & 09	468.0
15		Upper	09 & 08	205.0
16		Upper	08 & 07	338.0

3.2. Flow data

Since no gauges are available for the study site, the flow data is calculated from the daily precipitation data using SCS curve number method and Win TR20. For rainfall frequency analysis Log Pierson 3 Method was applied to the peak precipitation data of each month during 40 years (1974-2013). The histogram showing maximum monthly rainfall for the collected data is shown in Figure 3.

Fig. 2. Monthly Maximum Rainfall Histogram for period (1974-2013).



From these analyses, the peak rainfall for 2, 5, 10, 25, 50 and 100 return periods were calculated using Log Pearson type 3 distribution and it resulted in 9.60, 43.20, 91.50, 140.50, 190.90, and 299.70 cumecs respectively. WinTR-20 uses SCS curve number for calculating discharge values. Rated curve number and time of concentration were needed to run WinTR-20. The time of concentration was given by (Eq.1). The length (L) and slope (S) were measured using the DEM model.

$$Tc = \frac{0.0078L^{0.77}}{S^{0.385}} \qquad \text{Eq.1}$$

Where;
Tc = Time of concentration
L= Channel length in meters
S= Slope

Curve number is different for different land uses. To determine the weighted curve number, catchment area of Naray-Khwar was classified by ERDAS imagine software using a high-resolution land use file from Landsat website for Peshawar region (Fig. 4). The area for each land use was measured separately using QGIS. Rated curve number is given by (Eq.3) below;

$$\mathbf{RCN} = \frac{\mathbf{AL \times C1 + S \times C2 + R \times C3}}{\mathbf{100}} \quad \text{Eq.3}$$

Where;
RCN= Rated curve number
AL= % of agricultural land20%
S= % of settlements 23%
R=% of rocks57%
C1= Curve number 1
C2= Curve number 2
C3= Curve number 3

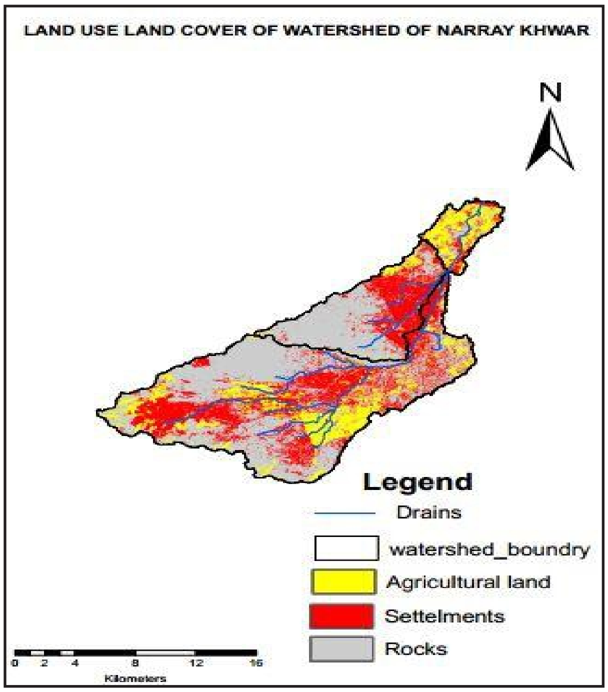


Fig. 3. Land use details on the course of Naray-Khwar.

4. HEC-RAS inputs

Hydraulic model HEC-RAS (Hydrological Engineering Centre – River Analysis System) was used during this analysis to evaluate water surface profile of Naray-Khwar. This model was developed by the US Army Corps of Engineers 2001. It is a one-dimensional model able to simulate steady, unsteady and sediment transport for movable boundary conditions. It has a special module to model water surface profile. The readers are referred to HEC-RAS manual 5.0.3 for further details. HEC-RAS required geometry and flow data of river. Geometry data contain number of x-sections upstream and downstream of bridge, distance between them and the roughness coefficient of the river and flood plain while flow data contain the discharge for different return periods. Number of x-sections depends of river variability.

4.1. River system schematic

Naray-Khwar was drawn on a reach-by-reach basis. River reaches were drawn in a positive flow direction from upstream towards the downstream. Each reach is identified by a unique name. After the river system schematic has been completed, the next step is the development of the river cross section.

5. Geometric input

Geometric data includes the station elevation points, bank stations and the downstream reach lengths for Left of bank & Right of bank. Each cross section taken at random interval is entered to derive the geometric boundary of Naray-Khwar. Manning coefficients (Chow, 1959) used for left over bank (LOB), Channel and Right Over bank (ROB) was taken as 0.04, 0.04 and 0.05 respectively. A value of 0.1 was used as contractions and 0.3 as expansion coefficient. The schematic diagram of the Khwar under consideration is shown in Figure 5 below

6. HEC-RAS validation

For HEC-RAS validation the flood data of 2014 having magnitude of 102.25 cumecs was used. The water surface elevation obtained from this flood using HEC-RAS was compared with the approximated observed flood levels obtained from water marks by the locals at some of the locations as shown in Table 3 below.

7. Steady flow input

Once the geometric input of the river is defined, the steady flow data is then entered into the HEC-RAS system in order to derive the steady water surface profile. In our case, the flow discharges calculated for 2-year, 5-year, 10-year, 25-year, 50-year and 100-year return period using Win TR 55 was used as flow data. The “known water surface elevation” boundary condition is defined for the downstream outlet.

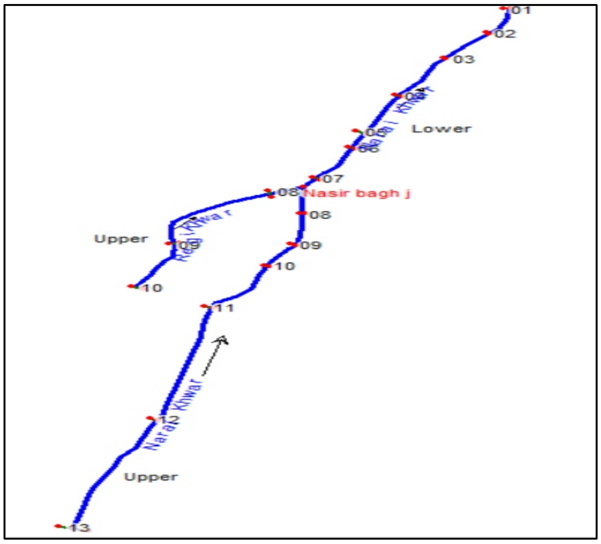
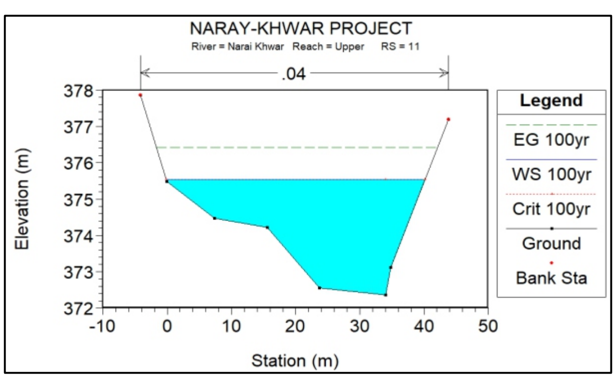


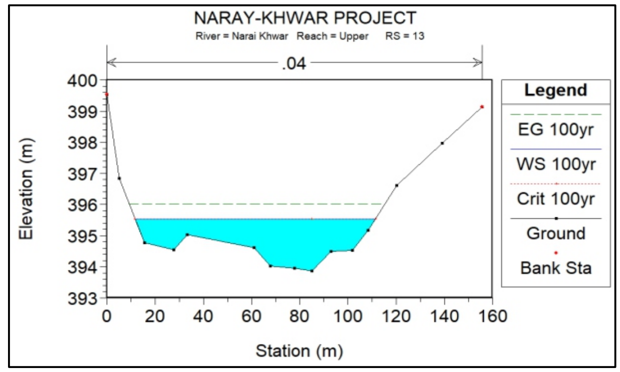
Fig. 4. River Schematic Showing Junction Point & X-Section Stations

8. Results

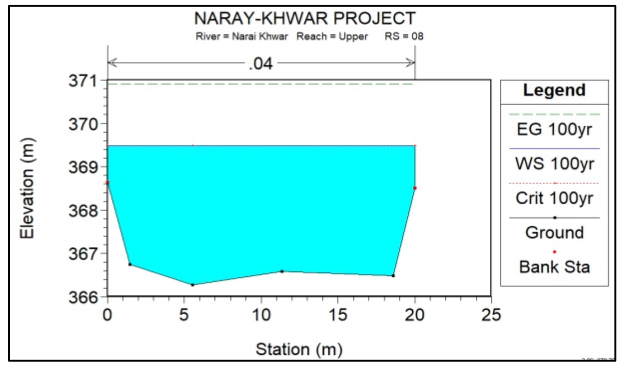
Simulating the steady flow conditions using HEC-RAS enabled us to determine the water level, flow velocity and energy line for all the cross sections for the given profiles of Naray-Khwar. Figure 6 illustrates various cross-sectional water levels as one move from upstream towards the downstream in “Naray-Khwar Upper”. Cross-sections on the upstream i.e., 11 and 13 near Hayatabad Ring Road are safe for 100 years flood, due to the high concreted overbanks and high ground level of houses Figs.6 (a) and (b). However, water surface profile exceeds the banks at cross section 08 by 0.9 meter and & 10 by 2.4 meter near Nasir-Bagh Bridge junction which is mainly due to low excavation depth of the channel (Fig.6(c)).



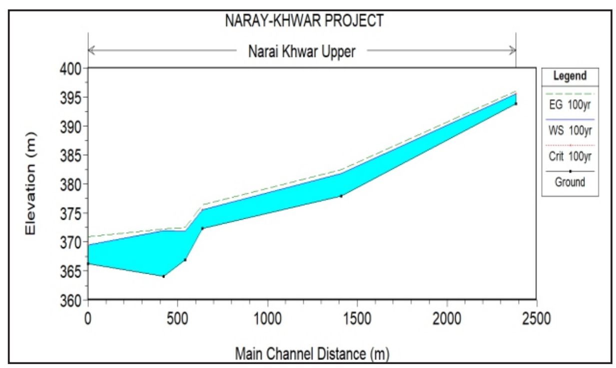
(a)



(b)

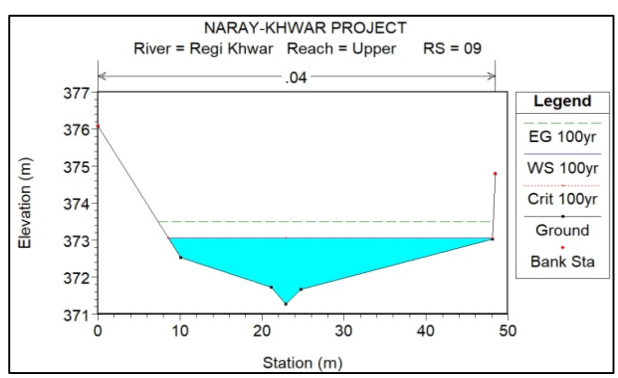


(c)

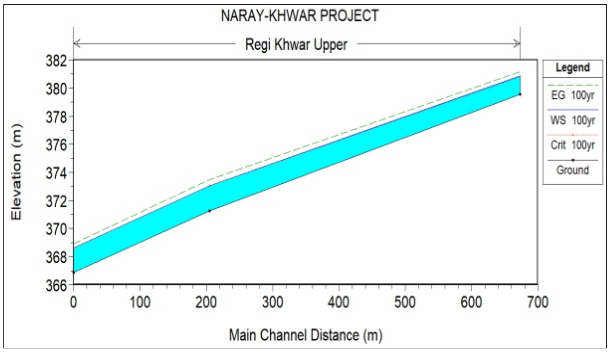


(d)

Fig. 5. Simulated water level along Naray-Khwar Upper. Where figure a, b and c shows simulated water profile along x-sections while figure d shows the same along channel profile.

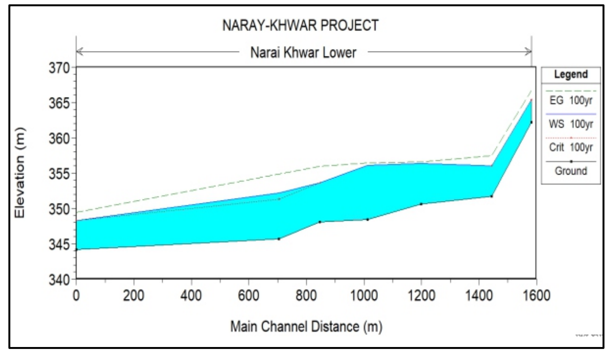


(a)



(b)

Fig. 6. Simulated water level along Regi-Khwar Upper Where figures a shows simulated water profile along x-sections while figure b shows the same along channel profile.

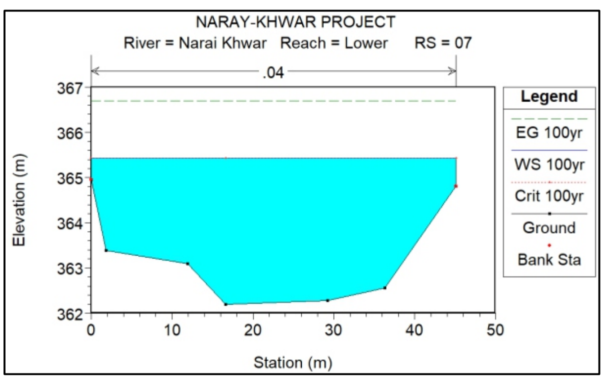


(c)

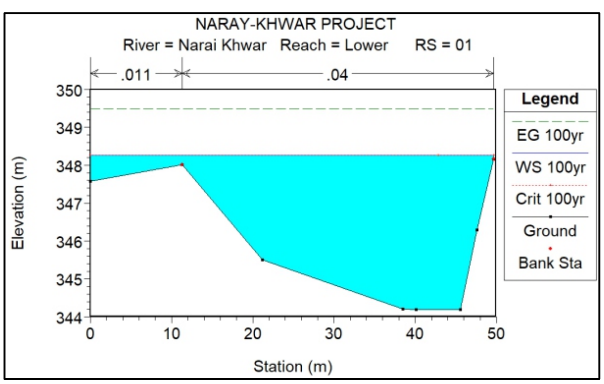
Fig. 7. Simulated water level along Naray-Khwar Lower Where figures a, and b shows simulated water profile along x-sections while figure c shows the same along channel profile.

Figure 7, shows area lying in the vicinity of Watershed_2. It is completely safe against a flood of return period 100 years since no overbanking is observed in Regi-Khwar Upper.

Figure 8 illustrates water depth along the course of Naray-Khwar Lower. Water from the upstream reaches combined under Nasir-Bagh bridge junction to produce a high discharge at the inlet of Naray-Khwar Lower. Simulation shows that the water surface level exceeds side banks in all cross sections.



(a)



(b)

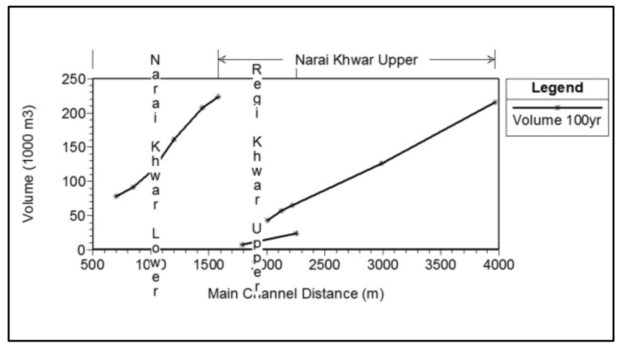


Fig. 8. Simulated flow volume in Naray-Khwar.

Figure 9 illustrates the direct proportionality of water volume to the channel length. Volume in the lower reach is relatively high as compared to the upstream reaches. The observed values at the outlets of Naray-Khwar Upper, Regi-Khwar Upper and Naray-Khwar Lower are 42840, 7280 and 77810 m3 respectively. High volume in the downstream channel makes it vulnerable to 100 years flood.

Figure 10 compares the velocity variation observed in all three channels of Naray-Khwar. Low velocity is observed in various sections along the river course. Such a condition gives rise to ponding of refuse and is characterized by severe water discoloration, foul odors, and an abnormally high mosquito population. Also, high velocity at the outlet of Naray-Khwar Upper explains the frequent drowning of Nasir-Bagh Bridge.

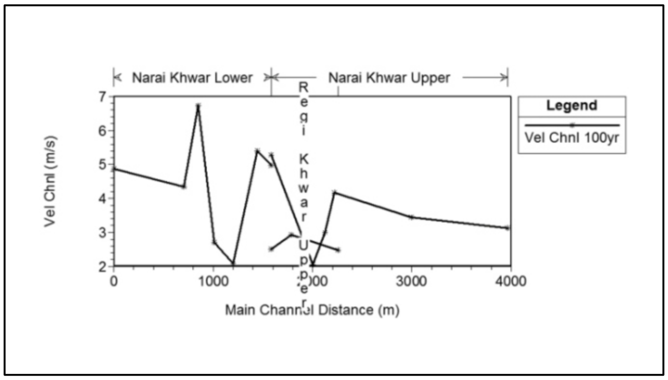


Fig. 9. Simulated flow velocity in Naray-Khwar

In order to compare the results for different Return Period, the cross section with water surface profile corresponding to 2, 25 and 100 years Return Period are shown in Figure 11, 12 and 13 respectively. The above comparison is made for x-section 7th of lower Naray Khwar, 08th X-section of upper Naray Khwar and 7th x-section of Regi Khwar. While the flow profile comparison for selected x-sections is also shown in table 2 below.

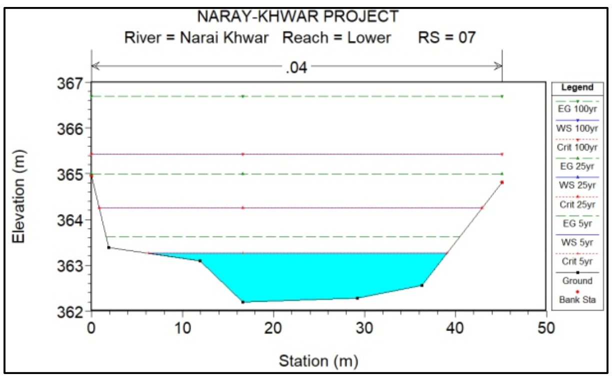


Fig. 10. X-section No 08, comparing Water Surface elevation for 2, 25 and 100 years Flood.

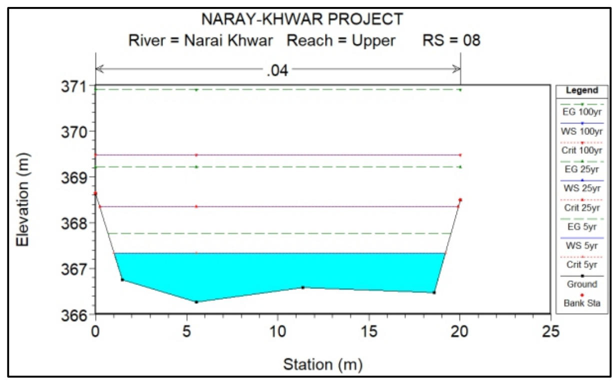


Fig. 11. X-section No 09, comparing Water Surface elevation for 2, 25 and 100 years Flood.

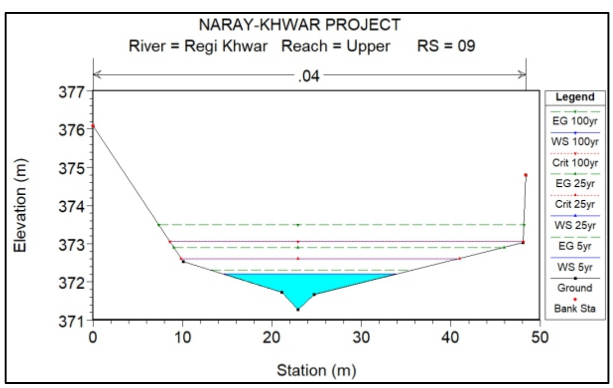


Fig. 12. X-section No 07, comparing Water Surface elevation for 2, 25 and 100 years Flood.

Table 2. Results obtained from HEC-RAS for X-sec of the three Khwar for Flood flows corresponding to 2, 5, 10, 25, 50 and 100 years return period.

River	Reach	River Sta	Profile	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Vel Chnl (m)	Flow Area(m^2)	Froude # Chl
Regi Khwar	Upper	9	2yr	2.1	371.27	371.86	1.19	1.77	0.84
			5yr	9.3	371.27	372.21	1.41	6.6	0.77
			10yr	18.9	371.27	372.39	1.78	10.63	0.87
			25yr	40.2	371.27	372.61	2.37	16.97	1.02
			50yr	64.4	371.27	372.83	2.64	24.4	1.02
			100yr	95.6	371.27	373.05	2.92	32.72	1.02
Naray Khwar	Upper	13	2yr	9.6	393.87	394.24	1.56	6.14	1
			5yr	43.2	393.87	394.69	1.96	22.02	1.01
			10yr	91.5	393.87	394.96	2.21	41.47	1.01
			25yr	140.5	393.87	395.13	2.47	56.78	1.02
			50yr	190.9	393.87	395.27	2.73	70.03	1.02
			100yr	299.7	393.87	395.53	3.12	95.91	1.02
Naray Khwar	Upper	11	2yr	9.6	372.35	372.88	1.97	4.86	1.01
			5yr	43.2	372.35	373.56	2.94	14.69	1.01
			10yr	91.5	372.35	374.14	3.55	25.76	1.02
			25yr	140.5	372.35	374.66	3.52	39.95	1.01
			50yr	190.9	372.35	374.97	3.8	50.24	1.01
			100yr	299.7	372.35	375.54	4.16	71.96	0.99
	Upper	8	2yr	9.6	366.27	366.8	1.78	5.4	1.02
			5yr	43.2	366.27	367.34	2.87	15.03	1.01
			10yr	91.5	366.27	367.89	3.63	25.22	1.01
			25yr	140.5	366.27	368.34	4.14	33.94	1.01
			50yr	190.9	366.27	368.75	4.54	42.06	1
			100yr	299.7	366.27	369.48	5.28	56.75	1
	Lower	7	2yr	12.7	362.2	362.64	1.78	7.13	1
			5yr	61.3	362.2	363.26	2.64	23.19	1
			10yr	130.9	362.2	363.73	3.22	40.68	1.01
			25yr	236.8	362.2	364.25	3.83	61.77	1.01
			50yr	359.8	362.2	364.75	4.31	83.47	1.01
			100yr	568.9	362.2	365.43	4.98	114.28	1
	Lower	1	2yr	12.7	344.19	344.76	2.03	6.25	1.01
			5yr	61.3	344.19	345.5	2.88	21.28	1.01
			10yr	130.9	344.19	346.07	3.57	36.62	1.01
			25yr	236.8	344.19	346.72	4.21	56.3	1.01
			50yr	359.8	344.19	347.35	4.67	77.12	1
			100yr	568.9	344.19	348.27	4.86	116.51	0.91

Table 3. Comparison of HEC-RAS simulated results with observed Water surface elevation of 2014 flood.

River	Reach	River Sta	Min Ch El (m)	W.S. Elev (m)	Observed W.S Elev.
Regi Khwar	Upper	10	379.56	380.88	380.38
	Upper	9	371.27	373.09	
	Upper	8	366.88	368.65	
Narai Khwar	Upper	13	393.87	395.01	
	Upper	12	377.96	380.29	
	Upper	11	372.35	374.33	374.13
	Upper	10	366.9	369.57	
	Upper	9	364.1	369.57	
	Upper	8	366.27	368	
Narai Khwar	Lower	7	362.2	363.56	363.13
	Lower	6	351.68	354	
	Lower	5	350.61	352.06	
	Lower	4	348.4	351.5	
	Lower	3	348.1	350.46	
	Lower	2	345.71	349.84	
	Lower	1	344.19	345.85	

9. Conclusion

In this research HEC-RAS was used for simulation of flood in three Khwar mentioned earlier. The results obtained shows that this model can perfectly predict the water surface elevations for any natural stream and can help in future flood prediction. It can also help in preparing the flood hazard maps and can identify the area subjected to flooding. The conclusions extracted from these results are discussed below:

1. Before the junction (joining point of Naray Khwar Upper and Regi Khwar Upper) at Nasir Bagh Road, All the cross section except cross section no 8 and 10 of Naray Khwar upper are safe even for a flood of 100 flood and there is no danger of any flooding. The safe cross sections include x-section no 8, 9 and 10 of Upper Regi khwar and 9, 11, 12 and 13 of Naray Khwar upper.
2. But after junction point, when it becomes Naray Khwar Lower at Nasir Bagh Bridge, the discharge is increased abruptly making all the cross sections vulnerable to overtopping for 100 years return flood.
3. This flood pattern was observed in the monsoon seasons while in other times of the year, the flow remain normal.
4. But the severe floods in monsoon are supported by some other factors that make the flood more devastating. These factors include poor waste management, illegal encroachments by the local people blocking the water way causing rising in water level and hence flooding and inadequate drainage system of the region.
5. High discharge entering into the downstream reach is halted by abrupt velocity changes in some parts of the channel. The HEC-RAS model has indicated sections susceptible to high water elevation level which is an indicator of the flooding event.

10. Recommendations

The following recommendations are made on the basis of the above analysis:

- Preparation of flood hazard map for these Khwars
- Remodeling of the whole Naray Khwar is the need of the day especially after the construction of Dean's Flats.
- Construction of sewage treatment plants to ensure that minimum refuse is discharged into the river.
- Construction of retaining wall along the banks of Naray-Khwar at low lying areas.
- Construction of detention ponds to mitigate the constraints of limited land for widening.

Authors' Contribution

Mujahid Khan proposed the main concept, supervised the work, involved in write up and did all the correspondence with JHES. Anas Uzair was involved in write up and analysis of results. Usama Ali conducted the actual work including survey, data collection and analysis. Wisal Khan was involved in *writing up the manuscript and editing.*

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