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# Flood Frequency Analysis and Hydraulic Design of Bridge at Mashan on River Kunhar

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**Abstract.** Kunhar River hydrology and hydraulic design of a bridge on this river are being studied using HEC-Geo-RAS and Hydrologic Engineering Centers River Analysis System (HEC-RAS). The river flows in the northern part of Pakistan and is 170 km long. On both sides of the river, there are residential settlements. The river hydraulics is studied by using 30-metre remotely sensed shuttle radar topographic mission - digital elevation model (SRTM DEM) and Arc Map. 32 cross-sections are imported from Geographic Information System (GIS) to HEC-RAS. On historical peak flow results, the extreme value frequency distribution is applied, and a flood is determined for a 100-year return period, with a discharge estimated as 2223 cubic metres. Three steady flow profiles are adopted for HEC-RAS, the first is for the maximum historical peak data, the second is for the 100-year return period, and the third profile is for the latter 100-year period with a safety factor of 1.28. With remote sensing-based assessments, the proposed location for a bridge is determined and then verified with a field survey which was physically conducted. The maximum water height estimated in the river is about 4.26 m. This bridge will facilitate about 50 thousand population of Masahan and its surroundings. It will create a shortest link between Khyber Pakhtunkhwa and Azad Kashmir and thus will enhance tourism and trade activities.

**Key words:** Flooding, River Hydraulics, Return Period, HEC-RAS, HEC-GEO-RAS, ASTER dem with 90 meters, DEM

## List of Acronyms

ANN – Artificial Neural Network
ARMA – Autoregressive Moving Average
ASTER – Advance Space Born Thermal Emission and Reflection
CFD – Computational Fluid Dynamics
DEM – Digital Elevation Model

ESRI – Environmental Systems Research Institute
GIS – Geographic Information System
HEC-RAS – Hydrologic Engineering Centers River Analysis System
SRTM DEM – Shuttle Radar Topographic Mission-Digital Elevation Model
SWAT – Soil and Water Assessment Tool
TELEMAC-2D – TELEMAC-MASCARET System
TIN – Triangular Irregular Networks

## 1. Introduction

Heavy rain falls occur during the monsoon season which is from June through September and show increasing trends of precipitation in the Kunhar River basin (Saifullah et al 2021). More frequent rains cause more frequent floods, resulting in increasing damages in the catchment area which is 2535 km$^2$. The processes of unsteady flow, open water flood forecasting, and flood routing were all investigated by Hicks and Peacock (2005). In another work, Graham and Angel (2001) proposed a flood estimating system for the Urumea catchment in Spain.

Duvvuri and Narasimhan (2013) used HEC-RAS, HEC-GEO-RAS and Arc GIS to map the depth and degree of flood immersion. Wangpimool et al (2013) used the Soil and Water Assessment Tool (SWAT) to model the rivers of Nan province in northern Thailand, and used it for numerical weather prediction for flash flood forecasting. The potential for heavy rainfall and flood inundation along the lower Kelani River was studied by De Silva et al (2012). Cook (2008) applied one and two-dimensional hydrodynamic models for flood mapping. Gunasekara (2008) used GIS to manipulate triangular irregular networks (TIN) and construct a hydrodynamic model, and also, to measure peaks through previous data and conduct a 50-year frequency analysis for flood hazard mapping.

Birkland et al (2003) identified an environmental damage under current law regulations, and re-checked policies to mitigate flood hazards. Bronstert (2003) studied the difference between hydrologic flood models and climate models, and then discussed trends for flood occurrence. Toth et al (2000) employed short-term rain forecast and stochastic Autoregressive Moving Average (ARMA) and Artificial Neural Network (ANN) model to obtain specific results. Tan et al (2005) used the SIMHYD model for six river catchments to construct flood hydrographs and carry out estimations based on previous events. Parker et al (2005) applied flood forecasting warning and response systems for residential areas, where a flood can damage people's properties and their livings. Charley (1988) used rainfall data taken from gauges, along with radar data, to perform flood forecasting. It was shown that radar data gave errors when compared with rain gauge data. Schreider et al (1997) proposed a rain-run off-model which was checked for two high-altitude catchments where snow quantity is greater, and showed that their model can estimate future climate changes and the hydrologic effect of the vegetation cover. Flood peaks and the amount of water are necessary for the calculation of the height of a bridge, and in this study flood peaks and maximum amount water are estimated by applying the Gumbel distribution method.

Kute et al (2014) modelled the Gangapur dam for flood control forecasting for 14 bridges downstream of the dam. For the study of flood zoning and flood control calculation, HEC-RAS was found to be the best choice. Using the HEC-RAS display with mapping, Jalali-Rad (2002) simulated a flood hazard for urban regions of Darabad, Tehran. Maidment and Tate (1999) used a planimetric flood plan to develop a base map and a HEC-RAS cross-section through digital model elevation for the study of flood mapping.

Horritt and Bates (2002) used flood hydraulic one- and two-dimensional models HEC-RAS, TELEMAC-MASCARET system (TELEMAC-2D) and LISFLOOD-FP for a 60 km section of a river for flood prediction. Fosu et al (2012) used GIS and HEC-RAS model and investigated them in Environmental Systems Research Institute's (ESRI) ArcGIS. Malik and Ahmad (2014) applied HEC-Geo-RAS for analysing the channel geometry, Advance Space Born Thermal Emission and Reflection (ASTER) DEM with 90 meters was used for the channel geometry data. The study found that HEC-RAS with GIS is the strongest tool for flood mapping and flood zoning. Salajegheh et al (2009) performed floodplain mapping utilizing HEC-RAS and GIS. In their study GIS was used to determine the channel geometry and cross section of a river in order to estimate the maximum height of water in the channel. Zaid et al (2019) investigated the problems of a bridge pier in their Computational Fluid Dynamics (CFD) simulation model. Yan et al (2017) investigated a hydrologic design by using the methods ENE, DLL, ER, and ADLL, with the latter three methods giving the design life of the project. Longer span bridges can be constructed by using composite cables, slotted girders, increasing deck stiffness and mass, and appropriate cable layout methods (Tsay 2021). The study area has a population of nearly 50,000, and at present has only a small bridge at its disposal, that can be used only by pedestrians, bicycles and motorbikes, but cannot be used by emergency services from Masahan. Therefore, a new bridge will greatly benefit the people living in the area, by significantly shortening the distance to the nearest large city of Muzaffarabad. The objective of this paper was to estimate flood peaks for different return periods, to evaluate hydraulic conditions in the study area, to estimate the cross-section of the river, and on this basis to propose the optimal location of a new bridge on the River Kunhar.

## 2. Materials and Methods

### 2.1. Flood Frequency

In order to estimate the flood return periods for 100 years, the flood frequency analysis is carried out. Statistical methods are applied to estimate flood characteristics for different return periods.

### 2.2. Gumbel Method

The maximum flood probability method is employed for estimating the distribution parameters. The fit of frequency model results to the data observed depends on the standard errors, the confidence limit of 95 percent, and the Chi-test. In order to express an uncertainty associated with sampling, statisticians use an interval of confidence. Millington et al (2011) used a statistical method for the upper Thames River.

The Gumbel distribution method is used in this work, and the formula is applied:

$$Q_T = \sigma K + \overline{Q}, \tag{1}$$

where $Q_T$ is peak flood at different return periods, $\sigma$ is standard deviation of Peak flood data, $\overline{Q}$ is mean of peak flood data, and $K$ is frequency factor.

$$K_t = \frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\left\{\ln\left(\frac{T}{T-1}\right)\right\}\right], \tag{2}$$

where $T$ is return periods and $K_t$ is frequency factor which depends upon return period $T$ (Amin et al 2016).

The formula for standard errors is

$$S_e = \left|\Sigma \frac{X_i - \overline{X}}{n}\right|, \tag{3}$$

where $X_i$ is an observed value, $\overline{X}$ is an estimated value $X$, $n$ is a sample size, and $S_e$ is a standard error given by

$$S_e = \frac{1}{\sqrt{n}}\,[1 + 1.139K_t + 1.100K_t \times 2]^{\frac{1}{2}}\, S_x, \tag{4}$$

where $S_x$ is the standard deviation in the flood Gumbel method, and is used to estimate a flood peak in flood frequency analyses on 20, 30, 50, 70 and 100 years of the return period.

### 2.3. HEC-RAS

TIN was used for the development of cross-section river geometry. The fundamental geometric data are processed and then imported into HEC-RAS with the help of HEC-Geo-RAS for additional hydraulic modelling. Pathan and Agnihotri (2021) used HEC-RAS for flood modelling with special reference through geospatial techniques.

### 2.4. GIS Data

By using DEM in GIS, the required RAS layers are created, which is a stream centerline by using collpas dual line from centerline tool; this tool can be founded in cartography toolbox. Channel banks, flow path, and XS cut lines are shown in Fig. 1.

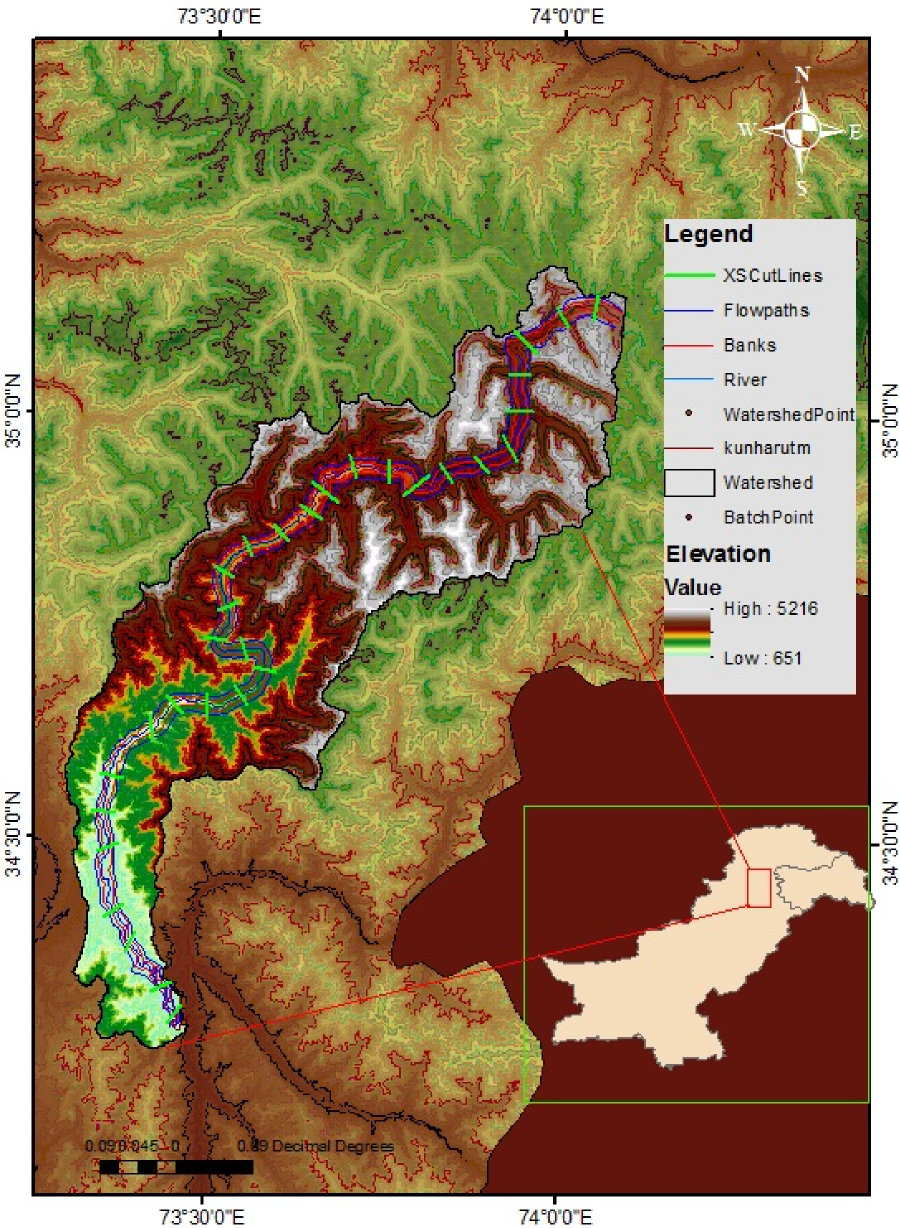



**Fig. 1.** River hydraulics map of Kunhar *River*

## 2.5. Geometric Data

Geometric data are based on stream junctions and cross-sections of river lengths, which are imported from HEC-Geo-RAS that appear on the river profile in geometric data with cross-section points.

### 2.6. Steady Flow Data

Three input profiles of steady flow data are shown in Fig. 2. The first one is the actual profile, the second profile is for the 100-year return period, and the third one is with a 1.28 factor of safety. The corresponding discharges are listed in Table 1.

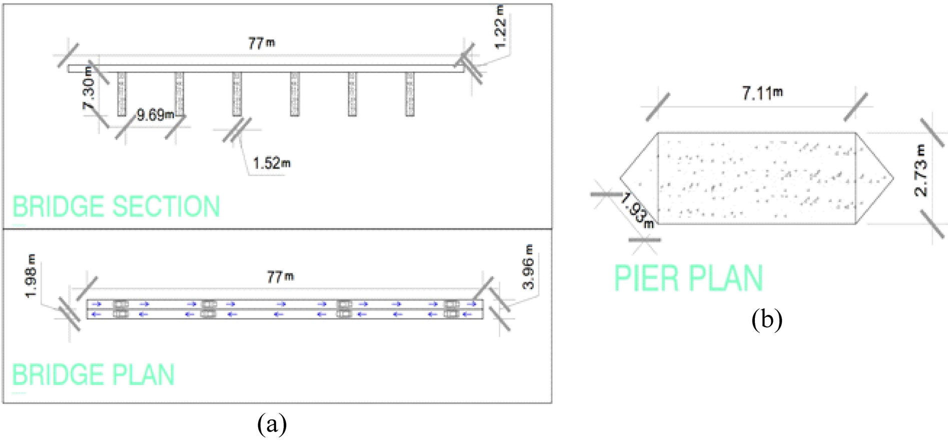



**Fig. 2.** (a) show cross section of bridge with its dimensions and bridge top view with available moving space for vehicles, (b) show pier plan and these piers are used under the bridge

**Table 1.** Steady flow input data of River Kunhar in HEC-RAS, with all profiles converted from CFS to cubic metres

| Steady Flow input | Discharge in cubic metres |
|---|---|
| Profile 1 (pf1) | 1415.84 |
| Profile 2 (pf2) | 2264.38 |
| Profile 3 (pf3) | 2831.68 |

### 2.7. Cross-section

Cross-section data are extracted from the digital elevation model and are later converted to TIN by using ARC-GIS and then Cross-section with all characteristics of the water imported from Geo-RAS to HEC-RAS.

### 2.8. Data Collection

Previous flood events data were collected from Water and Power Development Authority, Pakistan. The purpose of flood data collection was to check the previous maximum peak flood in the study are, and also to use them to estimate flood in a 100-year return period by means of flood frequency analyses. The data covering the years 1933–2013 were used in the flood frequency analysis. For the purpose of GIS, ASTER DEM 30 meters are used to extract the geometric data that is used in HEC-RAS cross-sections of the river, imported through HEC-GEO-RAS to HEC-RAS.

### 2.9. Hydraulic Design of Bridge

By using HEC-RAS Tool Bridge, a bridge is added with a deck at 3.96 m. The depth of deck is 1.2 m. This is a two-lane bridge, and each lane 1.98 m wide, including the pedestrian way. Pier width is 1.52 m, 6 piers are in the shape of a square nose so that the coefficient of flow around the pier is 2 – this value is taken from the manual of the HEC-RA, Chapter 5, Table 3. The distance between piers is added with the pier tools, and the span between one pier to another one is 9.69 m, determined by the length of a pre-stressed concrete beam that can give sufficient span length (Yadi et al 2019). A higher span length will provide smoother flow of water under the bridge. Nonlinear wave load in shallow water is assumed to act on the hydraulic structure (Ti et al 2019). There are five openings for water flow, and two are next to the abutments. The free flow curve has 50 points, the submerged curves have also 50 points. Each curve has a total of 20 points. In the cross-section, the maximum height of the water, with a safety factor, is 7 m when measured from the river base, which is 221.8 m from the middle of the river bed. And the discharge is 2831.68 $m^3$.

## 3. Results from Simulations

The Gumbel distribution method, briefly described in Section 2, was used to estimate the maximum flood peaks over the Kunhar River at Ghari Habib Ullah, and later to calculate the maximum flood height over Kunhar at the bridge modelled in HEC-RAS. For the frequency analysis on the River Kunhar, the Gumbel distribution is thought to be adequate. Peak discharge return periods of 5 to 100 years were considered. The peak discharge for a 100-year return period is approximately 2264.38 $m^3$, as shown in Fig. 3. For a 100-year return period flow, a safety factor of 1.28 was adopted for the hydraulic structure.

The upstream cross-section from the bridge site has all water profiles: pf1 for the actual discharge, pf2 for the 100-year return period, and pf3 for the 100-year period with the 1.28 factor of safety, respectively. The elevations expressed in metres are shown in Fig. 4. On the ordinate axis shown are the elevations, and the station locations are on the abscissa. The pf3 profile, with the factor of safety, is the highest profile in Fig. 4. The bridge height is above the highest water profile which is determined by the flood frequency with 100 years of the return period.

Fig. 7 shows rating curves for two different stations of the river. Such curves, determined on the basis of the elevations and the discharge of the river, are one of the methods to measure the discharge with the stage height. Table 2 shows different hydraulic parameters of the flow. The flow is steady when the E.G. slope of 255.6 m is equal to the bed slope. The maximum channel depth is 4.2 m, which is equal to the

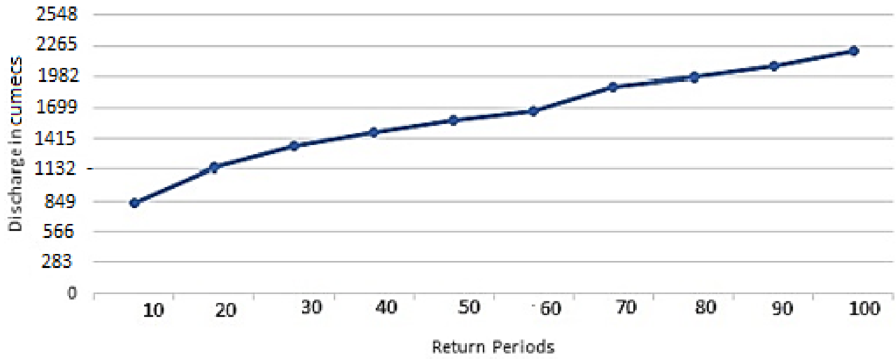



**Fig. 3.** Flood frequency analysis of Kunhar River

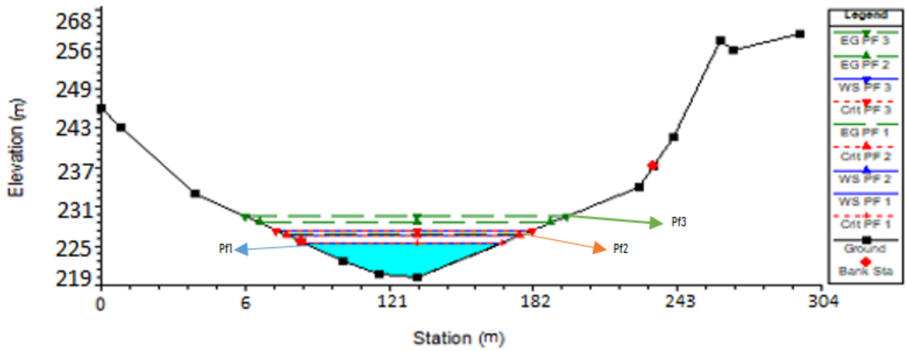



**Fig. 4.** Cross-section of the river with all simulated profiles water level and actual water level in River

water surface elevation of 255.14 m. The area of the channel is 528.92 $m^2$, and the wetted parameter is 133.29 m. The flow velocity is 2.76 m/s.

## 4. Discussions

By using the GIS and the techniques from the TIN model, the river cross-sections were generated, and the arch hydro tools were applied for the catchment area for the water shed delineation. Geometric data for the catchment were created by GIS, and then this data was validated with the actual site measurements. During site visits it was found out that the maximum population was living in the area where the bridge was proposed for construction. The catchment area was determined from the GIS.

The river bank and flow path were created using remote sensing surveys in GIS, which helped to define the size of each cross-section and the flow path. After the data was entered into HEC-RAS, minor cross-section modifications were required. After that, the model was parameterized and ran for three adopted profiles, with return periods of 100, 200, and more than 200 years. The three flood profiles were created

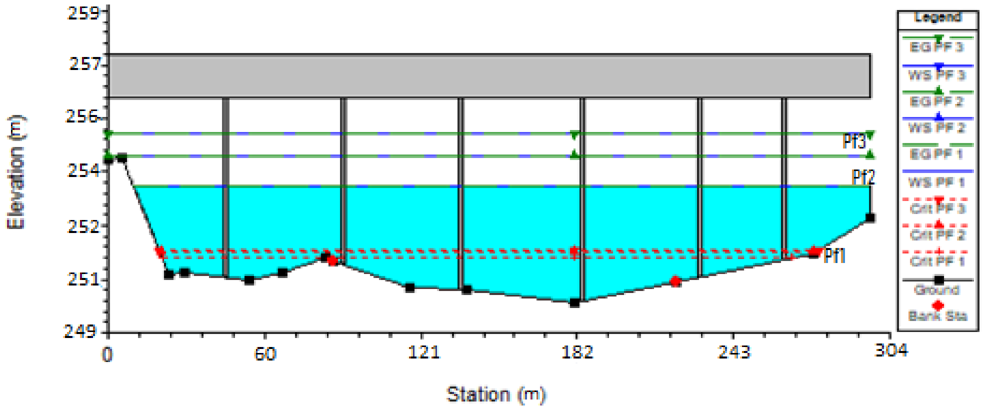



**Fig. 5.** Cross-section of river and bridge on the river with all profiles level and actual water level

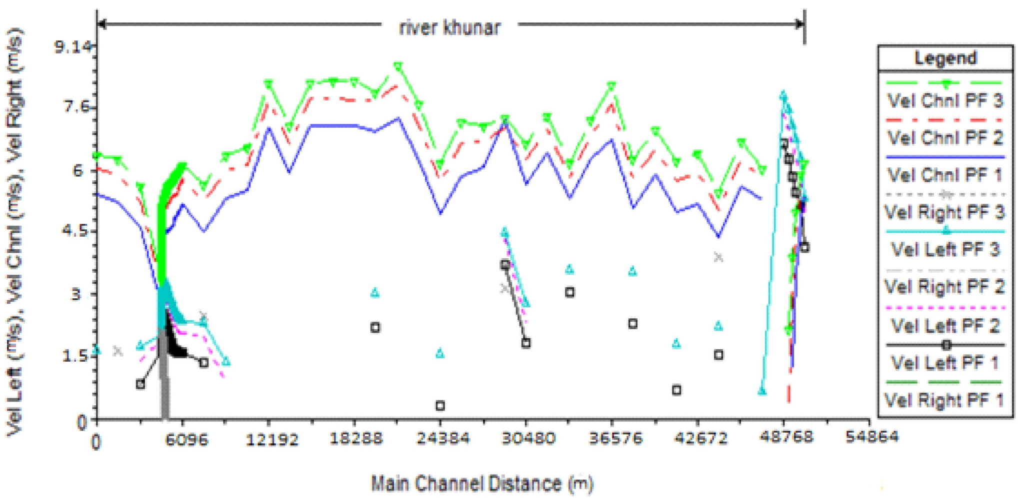
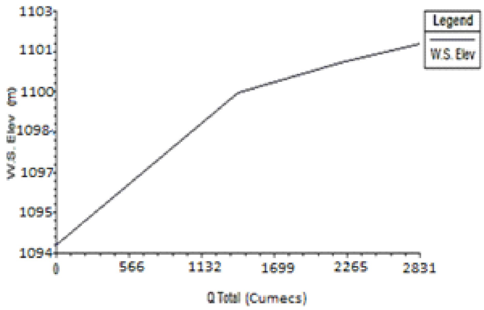



**Fig. 6.** General profile velocity with all profiles are shown in graphic form, with three different profiles as pf1 pf2, and pf3. The profile shows that the speed of the first profile is 5.4 m/s to 6.7 m/s and the third profile is 6.7 to 8.5 m/s

using the Gumbel flood frequency analysis. It represented in Fig. 5 and also contain bridge structure. Actual water level in the River shown as well as predicted water level also shown in mentioned figure.

The maximum height of water was 6 meters. The elevation difference along the Talhata, Ghari Habib Ullah link road, and the Muzaffarabad to Ghari Habib Ullah road, was 12 m. But the existing bridge is at the lowest elevation, which has the smaller height according to 100 years flood frequencies. So, it is required to replace that bridge, and the minimum safe height of the new bridge is required to be 7.3 m.



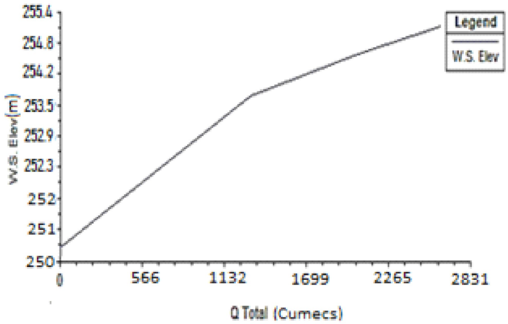




**Fig. 7.** Rating Curves of a different cross-section of Kunhar River

**Table 2.** Hydraulic parameters of the flow

| Plan: Plan 01 River Khunar RS: 20001.78 Profile: PF 3 | | | | | |
|---|---|---|---|---|---|
| E.G. Elev (m) | 255.6 | Element | Left OB | Channel | Right OB |
| Vel Head (m) | 0.460 | Wt. n-Val. | 0.030 | 0.022 | 0.030 |
| W.S. Elev (m) | 255.14 | Reach Len. (ft) | 1527.14 | 1527.14 | 1527.14 |
| Crit W.S. (m) | 253.88 | Flow Area (sq m) | 261.370 | 528.92 | 233.309 |
| E.G. Slope (m/m) | 0.000274 | Area (sq m) | 261.37 | 528.92 | 233.309 |
| $Q$ Total (cms) | 2831.6 | Flow (cms) | 537.13 | 1808.56 | 486 |
| Top Width (m) | 297.14 | Top Width (m) | 88.18 | 133.27 | 75.67 |
| Vel Total (m/s) | 2.76 | Avg. Vel. (m/s) | 2.05 | 3.419 | 2.081 |
| Max Chl Depth (m) | 4.36 | Hydr. Depth (m) | 2.96 | 3.96 | 3.08 |
| Conv. Total (cms) | 94348.99 | Conv. (cms) | 17896.75 | 60259.33 | 16192.93 |
| Length Wtd. (m) | 1527.14 | Wetted Per. (m) | 88.77 | 133.29 | 77.65 |
| Min Ch EI (m) | 250.78 | Shear (kg/sq m) | 2.63 | 3.56 | 2.68 |
| Alpha | 1.18 | Stream Power (kg/m-s) | 5.44 | 12.21 | 5.64 |
| Frctn Loss (m) | | Cum Volume (ha – m) | 2.86 | 136.78 | 3.48 |
| C & E Loss (m) | | Cum SA (ha) | 12.22 | 53.43 | 9.38 |

## 5. Conclusions and Recommendations

The river's water level rises only in the summer season, when mountain glaciers melt and rains start in the catchment area. According to historic records, the river's maximum flood was about 1439.83 cubic metres in 1990. Because the terrain is mostly hilly, floods are not as bad as they are in flat areas. The simulated river's peak discharge values are 1157.93, 1480.66, 1667.47, 1898.11, and 2210.38 cubic metres in 10, 20, 30, 50, and 100 years, respectively. The height of the bridge is adopted with a safety factor of 1.28. Based on the current research results, the design aspects of the planned Kunhar River Bridge have been worked out. The bridge spans 77 metres and is 3.96 metres wide, with pedestrian walkways on both sides and a 1.22 meter deep deck. Piers are 1.5 m wide and have a square nose. The piers and the bridge are the same height.

The distance from Masahan to Muzaffarabad via the existing Gotha Bridge is 19.5 km, and the distance via Ghari Habib Ullah Bridge is 69 km. However, by using the proposed location, the road distance between Masahan and its nearby villages to Muzaffarabad will be shorted by 8 to 9 km.

More gauges in the catchment area are required for getting more accurate results, as opposed to only two stations used in the research. Some societies have restrictions in place for people who live in flood plain areas, so there should be also restrictions for peoples living in flood hilly areas. For accurate performance, SRTM 30-meter DEM was used; however, the use of DEM with higher resolution is recommended.

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