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Channel Forming Discharge in Rivers: A Case Study of Jhelum River in Pakistan

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Abstract

It is generally believed that a range of flows or a flow regime is responsible for channel formation and maintenance rather than a single flow rate. Conversely, depiction of the channel-forming discharge as a single flow rate that represents the collective effects of a range of discharges is a convenient method for designing management schemes for controlled rivers. Three approaches are available for the quantification of channel forming discharge (Q_{cf}): effective discharge (Q_{eff}), bank-full discharge (Q_{bf}) and return interval discharge (Q_{ri}). In the present study the variability in the relative magnitudes of the three approaches of estimating Q_{cf} has been studied using literature review and by analyzing two reaches of Jhelum River near Hattian Bala Gauging Station and Azad Patan Gauging Station. The three approaches provide comparative values for non-incised river reaches having low flow variability and are having coarse beds. It has been observed that for the flashy hydrology, values of Q_{eff}, are usually higher than Q_{bf} and for the incised river reaches values of Q_{bf} are much higher than the Q_{eff}. The results of the study are in comparison with the results of previous studies regarding flashy hydrology and sand beds. The flow duration of the effective discharge for studied reaches is 13% to 4.6% of time or 48 days per year to 13 days per year. These results support the conclusion of Wolman and Miller (1960) that the effective discharge is a comparatively frequent flow that happens on an average of a number of days per year. This study can be utilized by local designers especially for designing hydraulic structures on Jhelum River.

Key Words: Channel Forming Discharge / Effective Discharge / Bank-full Discharge / Recurrent Interval Discharge

1. Introduction

It has been observed that alluvial rivers are continually changing to create a balance between the factors acting on them. Although not rigorously proven, the idea that alluvial channels in equilibrium are adjusted to accommodate a discharge of certain magnitude is generally accepted in engineering practice [14]. Inglis [27] termed this as the dominant discharge and explained that "dominant discharge is the discharge which controls the meander length and breadth." As alluvial rivers experience a range of discharges rather than a single discharge, Wolman and Miller [42] noted that, "It is logical to assume that the channel shape is affected by a range of flows rather than a single discharge." Soar and Thorne [36] with the help of previous studies [1, 2, 8, 9, 10, 22, 26, 27, 28] suggested that, "Channel-forming flow theory argues that there is a unique flow which, over a prolonged period, would theoretically yield the same bank-full morphology that is shaped by the natural sequence of flows." It is suggested by Thorne et al. [38] that, "If the underlying principle of time-event compression can be accepted in applied geomorphology, then the channel-forming flow is an attractive simplification and has wide application potential." Stable channel design, channel stability assessment and river management using hydraulic geometry relationships are some of the uses of a channel forming discharge. So, it is suggested [14] that appropriate quantification of channel forming discharge is the first step in river channel engineering. At least three approaches are available for the quantification of channel forming discharge (Q_{cf}): effective discharge (Q_{eff}), bank-full discharge (Q_{bf}) and return interval discharge (Q_{ri}).

It was proposed by Wolman and Miller [42] that the amount of sediment transported by flows of a given magnitude is dependent upon the nature of relationship between discharge and sediment load as well as the frequency distribution of the discharge events. Later, Andrews [3] discussed that, given a power correlation between discharge and sediment load and a log normal discharge frequency, the curve relating discharge to cumulative sediment load has a single maximum at some higher magnitude, but not extreme, discharge referred to as the effective discharge (Fig 1). Recently [14] it is defined that effective discharge as that discharge (or range of discharges) which, over a passage of time, transports the greatest quantity of sediment. It was further mentioned that Q_{eff} is computed by finding the maximum of the curve resulting from multiplying the flow frequency curve times its sediment discharge rating curve. Various studies [13, 29, 35] used a suspended sediment rating curve for computing Q_{eff}; others [4, 19] used a bed load sediment rating curve; and further, others [3, 6, 14] used total sediment load. Biedenharn et al. [7] provided a detailed computational procedure for the estimation of effective discharge. It is mentioned that streams dominated by suspended load, a best-fit regression curve, fitted to the data, may be adequate to produce a sediment load function which frequently takes the form of a power function.

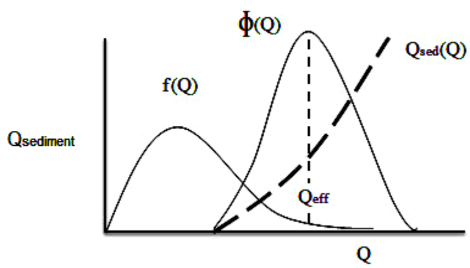

Fig.1 Wolman and Miller [42] Model of Effective Discharge (ϕ (Q) = Effective Discharge Curve, f(Q) = Flow frequency distribution) (Adopted from Doyle et al. [14])

Williams [41] after a detailed literature appraisal presented various definitions of bank-full discharge (Q_{bf}) based on the sedimentary features, requirements of measurements of boundary features and requirement of measured cross sections. Soar and Thorne [36] argued after detailed literature citation that, in a natural river the most appropriate definition is the discharge conveyed at the elevation of the active floodplain. Another definition of Q_{bf} is the elevation where the width to depth ratio is a minimum [21, 32, 43]. It is commented [14] that there is growing literature on the use of field indicators to identify bank-full stage and there can be wide variability in field determination of bank-full stage [12].

Various researchers have attempted to relate bank-full discharge and effective discharge with the specific return interval discharge (Q_{ri}). Wolman and Leopold [44] mentioned that the recurrence interval for bank-full flow in natural rivers with well-developed floodplains ranged between 1 and 5 years, using the annual maximum flood series. It is found that [45] bank-full discharge may have a frequency between 1.02 and 2.69 years in the annual maximum series. Williams [41] argued that only one third of thirty-six cases examined had recurrence intervals near the 1.5 year peak, the range being between 1.01 and 32 years. Shields et al. [34] discussed that, recurrence interval relations are essentially different for channels with flashy hydrology than for those with less variable flows. Literature review gives the impression that Q_{ri} tends to produce poor approximation of Q_{bf} [41] and of Q_{eff} [14, 29, 32].

Various studies [3, 14, 31, 35] attempted to compare the three approaches of channel forming discharge (Q_{cf}) i.e. Q_{eff}, Q_{bf} and Q_{ri} and suggested that Q_{bf} and Q_{ri} are a quick approximation of Q_{eff}. Some studies [14, 42] point out that in several stable channels these three approaches present comparable results. Whereas other studies [6, 15, 32, 35] indicate that the relationship between the Q_{bf} and Q_{ri} with Q_{eff} is not consistent. The above discussion suggests that there is need of further investigation on this subject particularly in the developing countries like Pakistan where this issue is quite new for the designers of river channels.

In the present study the variability in the relative magnitudes of the three approaches of estimating Q_{cf} has been estimated by using two case study and literature review. The results of this study are presented in the form of a summary and the approach will be useful for the designers of river channels.

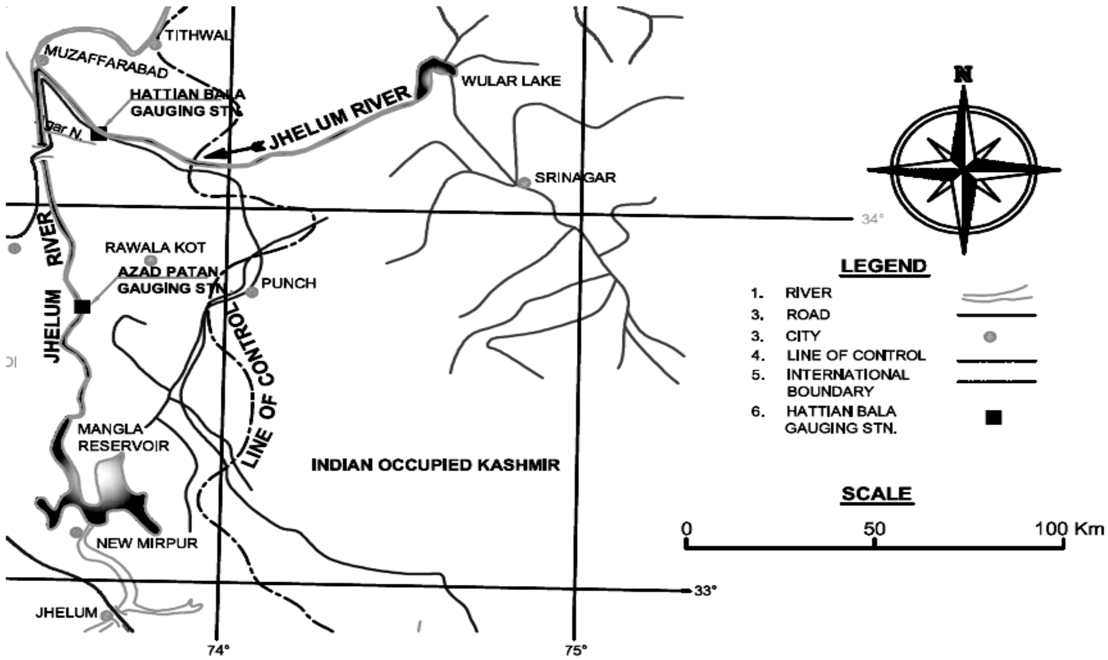

Fig.2 Layout of Jhelum River Up to Mangla Reservoir

2. Study Area

The Jhelum originates from the spring of Verinag, on the northwestern side of Pir Panjal and flows in a direction parallel to the Indus at an average elevation of 5,500 feet (1677m). Flowing in a north-west direction, it is joined by many streams before reaching the Wular lake. Below the Wular lake, the river runoff increases and flows in a south-east direction. The river valley starts contracting downstream of Baramola. At Chakothi, the river enters Azad Jammu and Kashmir (AJK) area and flows in a narrow valley taking a turn in a general north-west direction. On its steep course, the river takes a very sharp bend at Domel to flow in a general southward direction along-with its tributaries namely Neelam (Kishanganga) and Kunhar River (Figure 2). From Domel to Mangla, a distance of about 90 miles (144 km), two streams, the Kanshi and Poonch join the River Jhelum. The Mangla Dam has been constructed near the head regulator of Upper Jhelum Canal. From Mangla down to Rasul, several floodwater streams drain into the Jhelum. At Jhelum town the river turns southwestward along the Salt Range to Khushab, where it again bends south to join the Chenab River near Trimmu. The total length of the Jhelum is about 450 miles (725 km).

Although there are several gauging stations on the Jhelum River before joining the Chenab River, for this study Hattain Bala and Azad Patan Gauging stations (Figure 2) are selected due to the availability of reliable and long term hydrological data. River bathymetric survey is readily available for Hattain Bala gauging station, whereas, this survey could not be obtained for Azad Patan site. Both stream gauging stations are situated on a relatively straight reach of the river and hence measurements are reliable. The watershed area and mean annual flow for both stations is given in Table 1.

Table 1 Watershed Area and Mean Annual Flow

Gauging Station	Catchment Area	Mean Annual Discharge
	km^2	m^3/s
Hattian Bala	13,938	216.8
Azad Patan	26,485	838.3

3. Data Utilized

3.1 Discharge Data

Discharge data have been collected for Hattian Bala and Azad Patan gauging stations from Surface Water Hydrology Project (SWHP) respectively for the period of 35 years (1970 to 2004) and 27 years (1979 to 2006) which is available in the form of annual reports [5]. At both stations, there is staff gauge at which hourly stage is measured from 8:00 a.m. to 5:00 p.m., whereas flow is measured by using current meter, once a week, or twice per week in flood days. Descriptive statistics of the data collected was carried out and the missing values were inserted. Variation of flow throughout the year has been presented through hydrograph prepared by averaging the daily values of available record. For two gauging stations these have been shown in Figures 3 and 4. At both stations, the flows are maximum in the month of May and Minimum in the month of December.

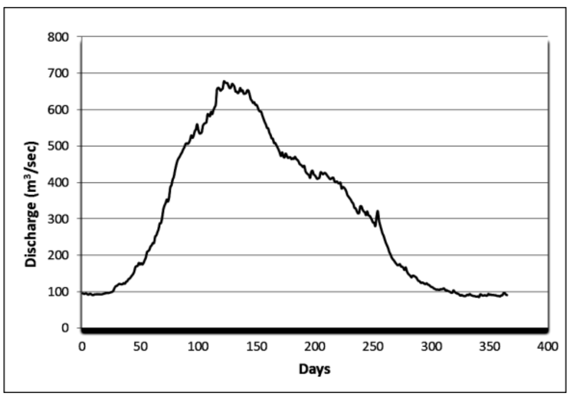

Fig.3 Variation of Average Daily Flows at Hattian Bala

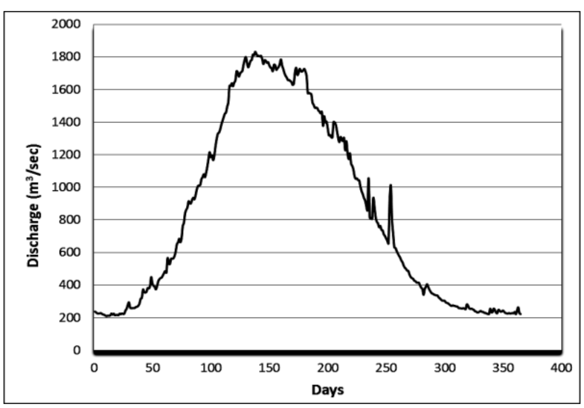

Fig.4 Variation of Average Daily Flows at Azad Patan

3.2 Sediment Data

Suspended sediment concentration is also measured at the gauging stations by using a depth integrated suspended sampler D-49 with a 62 lb weight. Sampling for water quality is taken at an internal of once per month. There is no cable-way and measurements are managed from a suspension bridge. Sediment concentration data was obtained from SWHP annual report [37] and was collected and digitized for the same period (1970-2006) for which discharge data were collected.

3.3 Bed Material Gradation

For the Hattian Bala gauging station a bed material sample was obtained from downstream of Hattian Bridge on the left bank of the river on April 16, 2008 during the site visit conducted as part of site investigation of Detailed Engineering Design of Kohala Hydropower Project. The sample was tested in the Laboratory of University of Engineering and Technology, Lahore. However for Azad Patan gauging station bed material samples were not physically collected but gradation was obtained from the Published Report [25].

Table 2 shows the bed material gradation of both the gauging stations.

Table 2 Bed Material Gradation

Gauging Station	Sand	Silt and Clay
	Percentage	
Hattian Bala	52	48
Azad Patan	57	43

3.4 River Bathymetric Survey

For the Hattian Bala gauging station the river bathymetric survey of the reach in proximity of the gauging station was conducted by International Sediment Research Institute, Pakistan (ISRIP) for the Kohala Hydropower Project during Jan-Feb of 2009 and published results in form of a report [24]. In the present study four river cross-sections have been used and are presented in Figure 5.

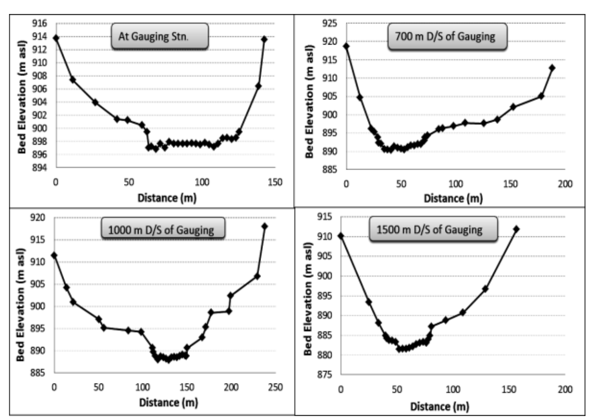

Fig. 5 River Cross-Sections of Study Reach

The longitudinal section of the River based upon the minimum bed levels of observed cross-sections, for a reach from Hattain Bala to 1.5km downstream, is presented in Figure 6.

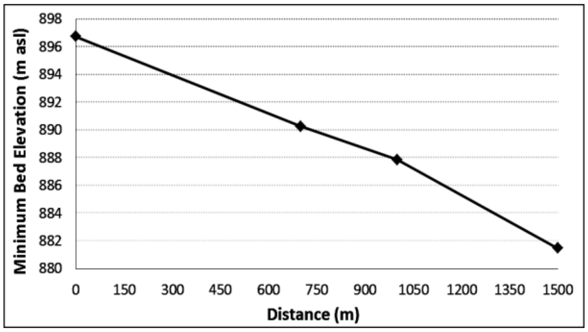

Fig. 6 Longitudinal Section of Jhelum River for Study Reach

For the Azad Patan gauging station, reliable river cross section data could not be obtained due to lack of time and resources.

4. Methodology

The study is divided into three steps namely, Data Collection, estimation of Channel Forming Discharge using three approaches i.e. Effective Discharge (Q_{eff}), Bank-full Discharge (Q_{bf}) and Recurrent Interval Discharge (Q_{ri}), estimation of variability in their relative magnitudes; and lastly discussion of results and comparison of the present study with the findings of previous studies obtained from a thorough literature review. The stepwise methodology adopted for this study has been presented in flow chart (Figure 7). The methodology adopted for the estimation of Channel Forming Discharge (Q_{cf}) using these three approaches is further elaborated below.

4.1 Effective Discharge (Qeff)

Effective discharge Q_{eff} has been determined from the flow-frequency distribution, and preparation of the bed-material load rating curve. The flow-frequency distribution and bed-material-load rating curve have been combined to produce a bed-material-load histogram which displays sediment load as a function of discharge for the period of record. The histogram peak indicates the effective discharge.

Flow-frequency distribution has been estimated by evaluating the flow record and stability of flow regime of Hattian Bala and Azad Patan gauging stations. Discharge range is calculated by subtracting the minimum discharge in the flow record from the maximum discharge. Discharge class interval is estimated by selecting 15 arithmetic classes and flow-frequency distribution is consequently determined by estimating the frequency of occurrence of each discharge class.

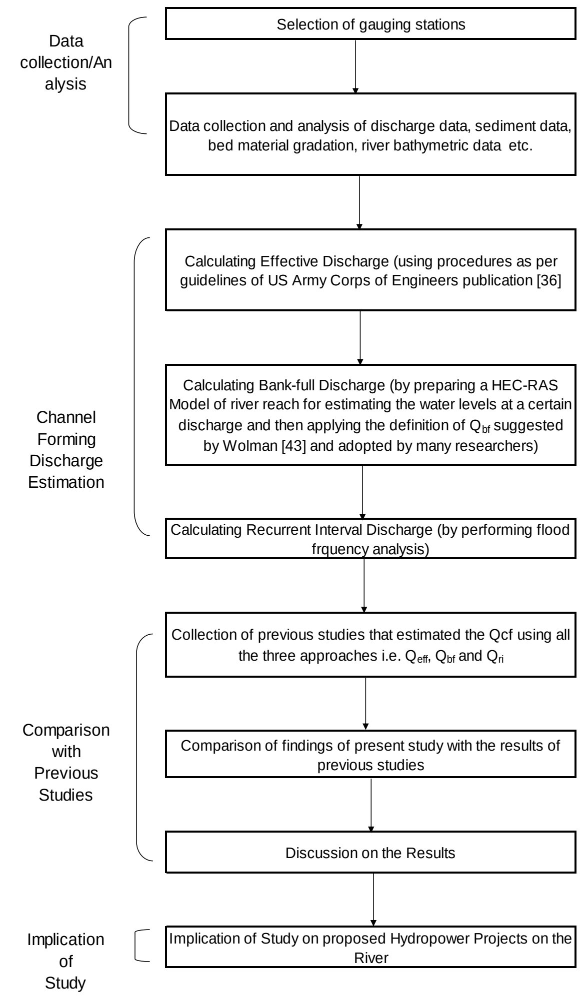

Fig. 7 Flow chart of the study

The bed material gradation curve suggests bed material load is predominantly due to suspended load (measured load) instead of bed load. It is suggested [36] that if sufficient (more than 10 years) sediment data (suspended load) is available then it can be utilized for preparing the bed material load rating curve after excluding the wash load. It has been suggested [16] that, wash load is usually 10% of the suspended sediment load. For this study, a power function best fit regression line, was fitted to the suspended sediment load data and the following is the equation for this regression analysis for Hattian Bala Gauging station;

$$Q_s = 0.3769*Q^{1.5994} \quad (1)$$

For Azad Patan gauging station;

$$Q_s = 0.0297*Q^{2.034} \quad (2)$$

Where,

Q_s = Sediment Load (tonnes/day)

Q = Discharge (m^3/s)

The bed-material-load histogram has been prepared by first calculating the representative discharge which is the arithmetic mean of each class of flow-frequency distribution. Bed material transport rate for each discharge class has been estimated by employing Equation 1 and 2. This load is multiplied by the frequency of occurrence of that discharge class to estimate the average annual bed material load transported by that discharge class during the period of record and consequently Q_{eff} corresponds to the peak of the histogram.

4.2 Bank-full Discharge (Qbf)

Bank-full discharge has been determined only for Hattian Bala gauging station by using the measured river cross-sections for estimating the different channel parameters like width, depth etc. for various discharges. HEC-RAS model has been employed for this purpose. Model has been calibrated for the reach by running at a flow rate for which measured water-surface line was available. Measured water surface elevations have been compared to the calculated water surface elevations and the Manning's n has been adjusted until the measured and calculated elevations are within 0.1 m. Once model is calibrated, a series of increasing flow rates are run through the reach. Bankfull discharge has been estimated by analyzing the variation of W (Top Surface Width), D (Hydraulic Depth) and W/D against water surface profile. The flow rates that created bankfull conditions for the location at gauging station cross section have been identified.

4.3 Recurrent Interval Discharge (Qri)

Flood frequency analysis of the annual maximum series for both the stations has been performed and a return interval of 1.5 years [36] has been computed using a Gumbel extreme value distribution.

5. Results

Flow duration curves for the two station based on available data has been shown in Figure 8 and 9 respectively, whereas, bed material load rating curves after excluding wash load is presented in Figure 10 and 11 respectively. By employing equations 1 and 2 time series plot for the sediment flow has been prepared to show the variability and range by using average daily flows for two stations. This has been shown in Figures 12 and 13 respectively for Hattian Bala and Azad Patan stations. By using the representative discharges from discharge classes in flow duration analysis and the bed material load rating curve, the bed material histogram has been prepared. Bed material load histogram has been presented in Figure 14 and 15 to illustrate the effective discharge that is estimated as 639 m^3/sec and 1262 m^3/sec respectively for Hattian Bala and Azad Patan gauging stations.

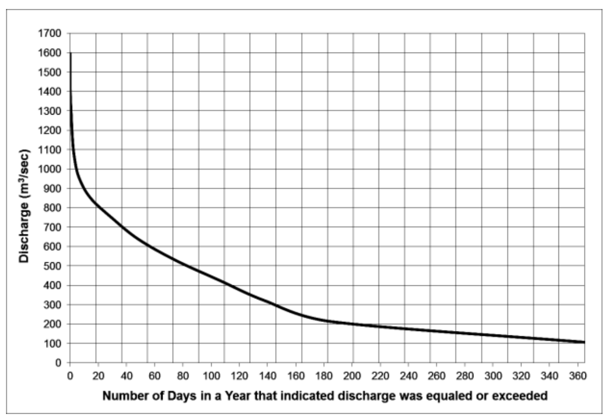

Fig.8 Flow Duration Curve of Hattian Bala

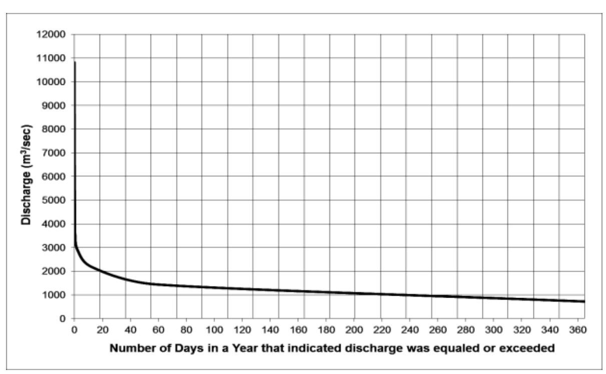

Fig.9 Flow Duration Curve of Azad Patan

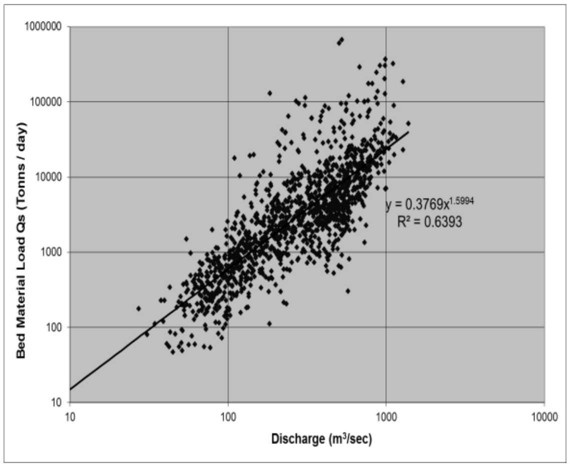

Fig.10 Bed Material Load Rating Curve for Hattian Bala

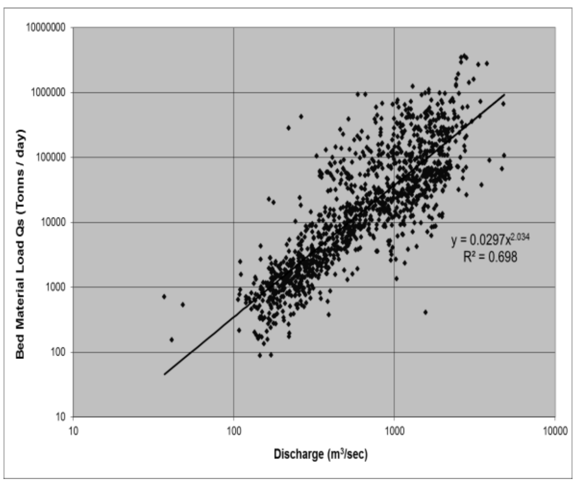

Fig.11 Bed Material Load Rating Curve for Azad Patan

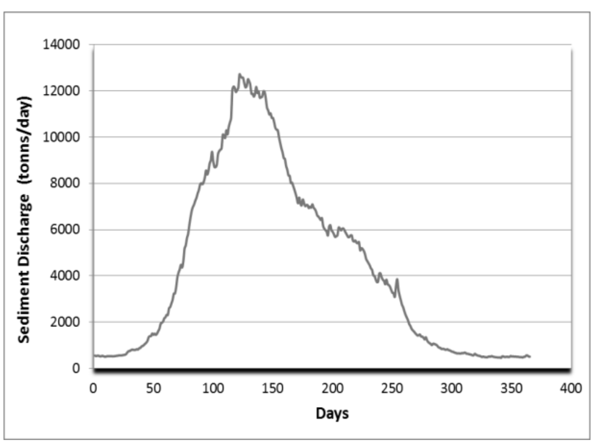

Fig.12 Variation of Sediment Discharge Based on Average Daily Flow at Hattian Bala

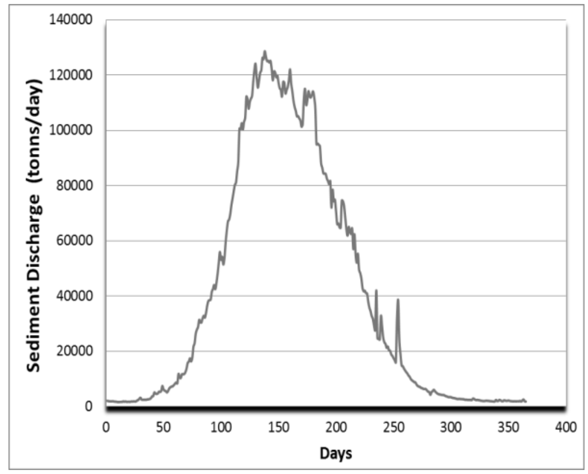

Fig.13 Variation of Sediment Discharge Based on Average Daily Flow at Azad Patan

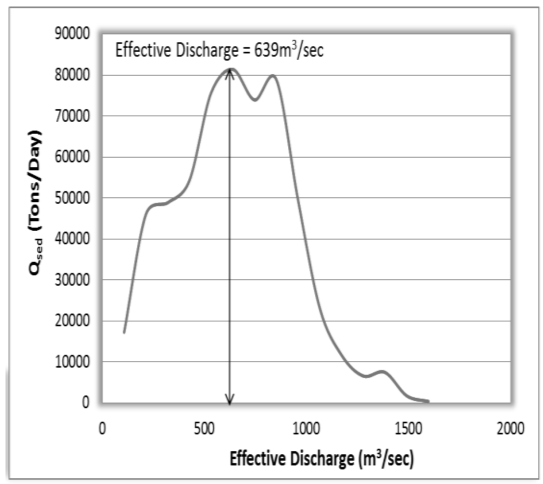

Fig.14 Bed Material Load Histogram Hattian Bala

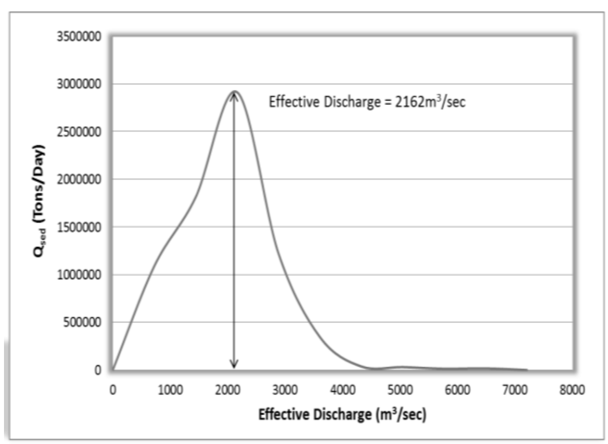

Fig.15 Bed Material Load Histogram Azad Patan

Bank-Full Discharge (Q_{bf}) has been estimated only for the Hattian Bala gauging station. For the estimation of Q_{bf} the HEC-RAS numerical model has been used and parameters required for the estimation of Q_{bf} for various discharges are shown in Table 3 and shown graphically in Figure 16.

Table 3 Output Parameters of Numerical Model

Q	WS Elevation	W	D	W/D	A
M^3/sec	m asl	m	m		M^2
100	899	61.48	1.21	50.81	74.22
200	899	63.10	1.74	36.26	109.60
400	900	68.16	2.53	26.94	172.28
600	901	82.94	2.85	29.10	236.69
800	902	91.31	3.19	28.62	291.26

Where,

W = Top Width
D = Hydraulic Depth, and
A = Flow Area

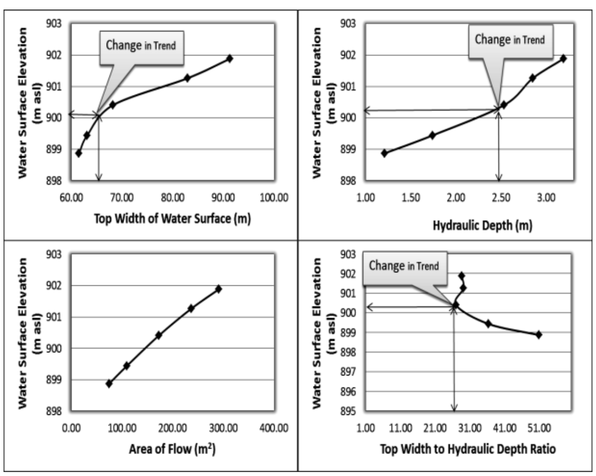

Fig.16 Variation of W, D, A and W/D against Water Surface Elevation

Analysis of Figure 16 for the estimation of bank-full discharge suggest that for the variation of W, D and W/D against water surface profile has a clear change in trend at the elevation of 900.4 m asl for the discharge of 400 m^3/s whereas flow area show no change in trend. So, by applying the definition of Q_{bf} as recommended by Wolman [43] this analysis suggests a Q_{bf} of 400m^3/s.

Relative magnitudes of the three measures of channel forming discharge (Q_{cf}) for the present study sites in the form of a bar chart has been presented in Figure 17. This comparison shows that Q_{eff} and Q_{ri} are greater than Q_{bf} for the Hattian Bala site, whereas, for the Azad Patan site Q_{eff} and $Q_{1.5}$ are having similar values.

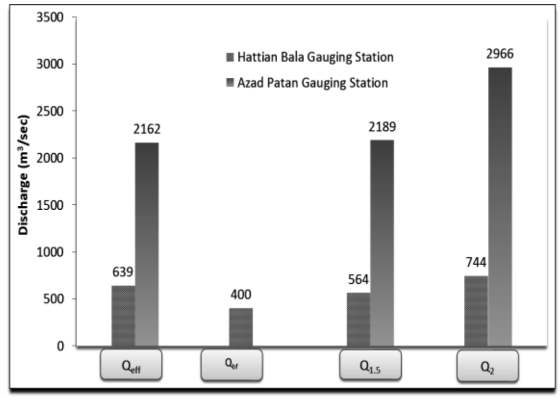

Fig.17 Comparisons of approaches for estimation of Q_{cf}

Frequency and duration of effective discharge events has been estimated as part of this research to study whether high frequency discharges are responsible for movement of bed material load. The effective discharge for the Hattian Bala is equaled or exceeded on average 13.2% of time or 48 days per year whereas, for Azad Patan these values are 4.6% and 13 days. This analysis further suggests that for the year 1996 daily discharge was equaled or exceeded effective discharge 141 days at Hattian Bala and this value for the Azad Patan for the same year is 78 days. For the Hattian Bala there are 7 years when effective discharge was not available throughout the years, whereas, for the Azad Patan there were 4 years when there was no Q_{eff} event. Further analysis suggests that for the Hattian Bala site more than 50 % of the suspended sediment load passing through this site at the effective discharge which occurred at least 48 days per year and is having a recurrence interval of 1.7 year, whereas, for the Azad patan site more 70% of suspended load are passing at Q_{eff} for the period of 13 days and having recurrence interval of 1.49 years.

6. Comparison with Previous Studies

It has been envisaged that relative magnitudes of various approaches of estimating channel forming discharge i.e. the ratios of Q_{bf} / Q_{eff} and Q_{ri} / Q_{eff} may be helpful indicators for the analysis of disturbance or instability as well as indicators of the course of geomorphic change in a catchment area. Thus, keeping in view this idea, data and results of some of those previous studies have been analyzed that discussed the relative magnitudes of three approaches of estimating channel forming discharge. These studies have been briefly discussed as under and quantitative results of previous studies along with results of present analysis have been presented in Table 4.

6.1 Andrew [3]

In this paper 15 gauging stations having diverse hydraulics and sediment characteristics were studied to compare the effective and bank-full discharges. Recurrence interval of the bank-full or effective discharge was also calculated in this study. Drainage area ranged from 51.8 to 9960 km^2 and median diameter of the bed material ranged from 0.40 to 86 mm.

Effective discharge was calculated for each gauging station by using the total sediment load instead of using bed load (Emmett and Wolman, 2001) or suspended sediment load (Simon et al., 2004). A total sediment transport rating curve was prepared for each station by adding measured suspended sediment discharges to bed load sediment discharges calculated using Mayer-Peter and Muller equation. The results of the study show that at the studied stations the effective discharges were equaled or exceeded on average between 1.5 days per year (0.4% of the time) and 11 days per year (3% of time). For the estimation of bank-full discharge river cross sections were measured for each gauging station. The bank-full discharge was defined as the discharge which filled the channel to the level of the floodplain. It was concluded that for each station ratio of Q_{bf} / Q_{eff} is nearly unity and bank-full discharge is having a recurrence interval greater than 1.75 years or less than 1.25 years. It was further discussed that there “does not appear to be a common frequency of occurrence for bank-full discharge”.

6.2 Nolan et al. [31]

Data from five gauging station of erodible mountainous terrain with high seasonal rainfall were studied in this paper. Drainage area of the gauging stations range from 420 km^2 to 5457 km^2 and mean daily flow range from 9.4m^3/sec to 155 m^3/sec.

Bank-full and effective discharges were calculated and the magnitude and frequency of suspended sediment discharge were estimated. It is important to note that bed load was not included in computing the effective discharge due to the fact that in two cases it did not change the values of magnitude and frequency of sediment transport. The result of the study show that majority of suspended sediment were transported by relatively large infrequent events i.e. 2 to 4 days per year and having recurrence interval of 3 to 16 years. The ratio of Q_{bf} / Q_{eff} was ranging from 1.35 to 4.42. This shows that bank-full discharges are very high than the effective discharge which is different from most of the other studies. The reason of this phenomenon as explained in the study was “because of floodplain formation appears to be due more to overbank deposition during the large sediment laden discharges than to lateral channel migration and point bar formation”.

6.3 Emmett and Wolman [19]

Three approaches of estimating channel forming discharge were estimated for five snow melt dominated, gravel bed rivers having drainage areas at sites ranged from about 55 to 4950 km^2 and median bed particles d_{50} ranged from 40 to 173 mm.

It was emphasized that channel maintenance is mostly concerned with bed load. Due to this reason Q_{eff} was estimated based on the bed load measurements instead of using suspend sediment load. Bed load transport rates were measured with Helley-Smith bed load sampler and subsequently bed load rating curves were prepared for five river reaches. Values of the bed load rating exponents ranged from 2.30 to 5.06. Q_{bf} was estimated by using the definition as that flow, when water just began to overtop the floodplain. The ratio of Bank-full discharge to effective discharge, Q_{bf} / Q_{eff}, ranged from 0.76 to 1.02. It was noted that as exponent of the bed load rating increases from typical to steeper value, effective discharge increases from near bank-full discharge to 1.3 bank-full discharges. Recurrence interval of the bank-full discharge was determined by using log Person analysis and was noted that values range from 1.5 to 1.7 years.

6.4 Simon et al. [35]

Data from more than 2900 sites were collected to analyze the sediment transport that is mainly pertinent with the new focus on stream restoration activities and the urgency in developing water-quality criteria for sediment. Eco-region concept was employed by using the historical flow and suspended flow data. It was discussed that channel forming discharge represents long term sediment transport conditions and designated this flow as potential metric for sediment transport conditions. It was further mentioned that “flow of a given frequency and recurrence interval is perhaps more appropriate to integrate suspended-sediment transport rates for the purpose of defining long term transport conditions at sites from diverse regions”. In this study bank-full discharge and effective discharge have been used interchangeably.

Effective discharge and its recurrent interval were calculated for the selected 500 sites. Effective discharge was calculated to represent the suspended sediment transport by applying the concept of Wolman and Miller [42], whereas, recurrent interval discharge was calculated by using annual maximum flow series and by applying Log Pesrson Type III distribution. Results of this study show that for a given eco-region, the median recurrence interval of effective discharge for suspended sediments ranges from 1.1. to 1.7 years. 1.5 year return period discharge for all the study sites were calculated and ratio of effective and recurrent interval discharge (Q_{eff} / $Q_{1.5}$) were observed. It was noticed that for various eco-regions median ration of Q_{eff} / $Q_{1.5}$ were between 0.6 to 1.3. It was perceived that 1.5 year return period discharge is reasonable measure of estimating effective discharge.

6.5 Doyle et al. [14]

In this study four river reaches representing variable hydrology and geomorphic conditions were studied to compute Q_{eff}, Q_{bf} and Q_{ri}. Two river reaches LC-1 and CR, were not stable due to changes in watershed that cause increase in runoff and extensive channelization for flood control respectively. Whereas, rest of the two reaches LC-S and TR were stable. As far as hydrology of the four river reaches is concerned, LC-1 and LC-S have flashy hydrology and CR and TR receive runoff dominantly due to spring snowmelt.

In this paper [14] Q_{bf} and Q_{ri} were compared with Q_{eff} to study the relative magnitudes of the three measures of Q_{cf}. Q_{eff} was calculated by multiplying the flow frequency curve times the sediment discharge rating curve. Both bed load and suspended sediment load were used for the estimation of sediment discharge rating curve. Q_{bf} was estimated by utilizing field survey cross sections in HEC-RAS hydraulic model. Q_{ri} was estimated by using Log-Pearson Type-III distribution for flood frequency analysis using annual peak discharges. It was revealed that three approaches were in close agreement at TR site (Q_{bf}/Q_{eff} = 1.04, Q_{ri}/Q_{eff} = 1.15) and wide variation for other three cases. It was noted that Q_{bf} and Q_{ri} (2 year recurrence interval flood) were greater than Q_{eff} for all sites except for TR. It was further noted that Q_{bf} was much greater than Q_{eff} for the two incised channels. Regarding the duration of Q_{eff} event it was noted that CR experienced flows greater than or equal to Q_{eff} 78 days annually whereas other sites had maximum values of only 24-36 Q_{eff} days per year. It was noted that flashy streams experienced frequent but short duration effective discharge events whereas snowmelt systems had fewer but longer Q_{eff} events.

7. Discussion and Conclusions

The above comparative review of literature regarding the study of relative magnitudes of various approaches of estimation of channel forming discharge suggest that, instead of addition of abundant data on flow duration, satisfactory quantitative comparison is challenging. This is due to the fact that similar data on sediment characteristics and transport, flow duration and channel features do not exist consistently. The analysis of the Table 4 suggests that three approaches provide comparative values for non-incised river reaches having low flow variability and are having coarse beds. It has been observed that for the flashy hydrology values of Q_{eff} are usually higher than Q_{bf} and for the incised river reaches values of Q_{bf} are much higher than the Q_{eff}.

The ratio of Q_{bf} / Q_{eff} and Q_{ri} / Q_{eff} for the studied reach is 0.63 and 1.2 respectively for Hattian Bala station, whereas, Q_{ri} / Q_{eff} for Azad Patan is 1.4 and Q_{eff} is approximately equal to $Q_{1.5}$. These results are in comparison with the results of previous studies regarding flashy hydrology and sand beds. For the case of Hattian Bala site Q_{bf} is about 40% less than the Q_{eff} which is due to the reason that floodplain formation appears to be due to lateral channel migration and point bar formation.

It is clear from the above analysis and previous literature review that for the estimation of Q_{eff}, hydrology data, sediment data and sediment gradation is required, whereas, for the estimation of Q_{bf} channel survey hydraulic analysis and model calibration using observed stage discharge relation is required and for the Q_{ri} historical hydrology for flood frequency analysis is needed.

It is evident from the literature review [12, 36] that choice of the suitable method will be based on availability of data, physical features of the location, time and funding limitations and scope of study. It has been mentioned by Copeland et al. [12] that, "If possible, it is recommended that all three methods be used and cross-checked against each other to reduce the uncertainty in the final estimate." Keeping in view these facts Hattian Bala gauging site has been analyzed using three approaches and Azad Patan gauging site by using two approaches i.e. Q_{eff} and Q_{ri}.

Soar and Thorne [36] suggested that, the method used should have general applicability, the capability to be applied consistently, and integrate the physical processes responsible for determining the channel dimensions. Tilleard [39] noticed that effective discharge model offers an association between the physical processes responsible for shaping the channel dimensions like the hydraulic characteristics of the channel, hydrologic characteristics of the catchment, and the geomorphic characteristics of the river reach. Moreover, for a provided hydrological regime, effective discharge analysis permits estimation of sediment budget of a river reach and provides greatest information both for channel stability analysis and channel design, whereas, this type of analysis is not possible by employing other parameters of estimating Q_{cf} like Q_{bf} and Q_{ri}.

It has been recommended that care should be made when applying the concept of channel forming discharge (Q_{cf}) particularly for incised system with flashy hydrology. Although mean values of Q_{bf}/Q_{eff} and Q_{ri}/Q_{eff} are nearly unity in many studies [3, 33, 35] but it has quite large variation among various sites. Therefore, one may not assume that Q_{eff}, Q_{bf} and Q_{ri} are similar. It has been observed that deviance from equality among three Q_{cf} measures is pronounced in river systems with high human interventions. The deviation of measures of channel

Table 4 Comparison of Various Studies (adopted from Doyle et al. [14])

Number of Sites	Hydrology	Channel Type	Bed	Q_{ri} / Q_{eff}	Q_{bf} / Q_{eff}	Source
15	Perinnial	Mountain streams	Sand and gravel	$Q_{1.18} < Q_{eff} < Q_{3.26}$	0.90-1.40	Andrews [3]
5	Perinnial	Stable, incised	Gravel	$Q_{1.2} < Q_{eff} < Q_{16}$	1.3-4.4	Nolan et al. [31]
5	Snowmelt	Mountain streams	Gravel and cobble	1.5-1.7 [2]	0.76-1.02	Emmett and Wolman [19]
10	Flashy	Unstable, incised	Sand and gravel	0.37-1.79 [2]		Simon et al. [35]
1	Snowmelt	Stable, nonincised	Gravel	1.15 [1]	1.04	Doyle et al. [14]
1	Snowmelt	Stable, incised	Gravel	1.93 [1]	5.25	Doyle et al. [14]
1	Flashy	Stable, nonincised	Sand and gravel	1.21 [1]	0.56	Doyle et al. [14]
1	Flashy	Unstable, incised	Sand and gravel	1.12 [1]	3.21	Doyle et al. [14]
1	Flashy	Mountain streams	Sand, silt and clay	$Q_{1.5} < Q_{eff} < Q_2$ 1.2 [1]	0.63	This Study
1	Flashy	Mountain streams	Sand, silt and clay	$Q_{eff} \approx Q_{1.5}$ 1.4 [1]		This Study

[1] Q_2 / Q_{eff} based on annual maximum series

[2] Return interval for Q_{bf} which was very close to Q_{eff} in this case

[3] Based on partial duration series

forming discharge may be a useful parameter of channel stability assessment. It is therefore recommended that where data availability, time and funding permits, channel forming discharge should be selected based on all the three parameters of its estimation.

The channel forming discharge (Q_{cf}) has practical utility and now a days mostly employed as the representative value for stability assessment and channel design [34]; is utilized for the design of hydraulic structures, and it is used in various theoretical models for predicting the stable slope upstream of grade control structures such as check dams and bed sills etc. [20]. In the same way, the concept of Q_{cf} can also be utilized in the Pakistan especially for the reaches of Jhelum River which is the one of the most important tributary of the Indus River. The study of estimating Q_{cf} will be helpful for the design of future hydraulic structures and channel stability analysis. Due to the fact that concept of Q_{cf} is quite new for the design engineers in Pakistan and river structures are usually not designed by applying the concepts of theory of channel forming discharge. Therefore, it has been envisaged that this study may open a new discussion in the engineering community for adopting state of the art design approaches as practiced worldwide. It is felt that in depth studies are further required by analyzing data of additional gauging stations of the Jhelum. In addition, similar studies may be undertaken to analyze the other river basins of Pakistan before adoption of these approaches by practicing design engineers in the country.

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