Geomorphic Effectiveness of High-magnitude Floods on the Tapi River: Evaluation based on Flood Hydrographs and Stream-power Graphs

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Abstract

In this paper an attempt has been made to quantitatively evaluate the geomorphic effectiveness of three large-magnitude floods that occurred in 1959, 1968 and 1969 in the lower Tapi Basin. Flood hydrographs available for these and other flood events show that the duration of floods can range from 6 to 10 days, and in exceptional cases up to 15 days. Geomorphologically, the channel response to such long-duration floods is likely to be significant especially in alluvial reaches in terms of bed and bank erosion as well as coarse sediment transport. The temporal variations in specific stream energy over the flood period were evaluated for these three flood events by constructing stream-power graphs. The flood hydrographs, the channel slope and the hydraulic geometry equations were used to compute the unit stream power and to construct the stream-power graphs. The graphs derived for two great and one common floods indicate that the power per unit area during such fluvial events is sufficiently high for several tens of hours to produce substantial changes in the alluvial sections of the Tapi River.

Introduction

The measurement and assessment of the geomorphic effectiveness of flows of different magnitude is one of the important themes in modern flood geomorphology. The effectiveness of events in shaping landforms is generally measured by the absolute magnitude of flows, by the frequency with which they occur, and by the amount of suspended sediment they transport (Wolman and Miller, 1960). In recent years, the potential of flood flows has been as-sessed in terms of the channel boundary shear stress and stream power per unit boundary area (Baker and Costa, 1987), as well as the flood flow duration (Costa and O'Connor, 1995), rather than absolute flood magnitude alone. Costa and O'Connor (1995) demonstrated that striking contrasts in river response to large floods on the same river or on different rivers could be attributed to the duration of the event and to its hydraulic characteristics. They suggested the

construction of a 'stream-power graph' from channel geometry, discharge rating curves, and flood hydrographs. Such graphs give a much better idea about the potential for a flood to be geomorphologically effective.

In certain hydro-geomorphic environments, such as the monsoonal tropics, floods play a dominant role in shaping the landscape (Wohl, 1992; Gupta, 1995; Kale, 2003). Infrequent, large floods that occur at an interval of several decades are associated with much higher levels of power expenditure and thus are capable of producing major channel changes and movement of coarse sediments (Gupta, 1995; Baker and Kale, 1998; Kale and Hire, 2004). However, very few attempts have been made to quantitatively evaluate the geomorphic effectiveness and examine the impacts of large-magnitude floods on monsoonal rivers. The main objective of this paper, therefore, is to quantitatively evaluate the geomorphic effectiveness of large-magnitude floods recorded on a flood-dominated monsoonal river, namely the Tapi River in central India.

Geomorphologic characteristics of the Tapi Basin

The Tapi River is the second largest west flowing river in India in terms of catchment area (65,145 km²). The basin is elongated and asymmetrical. All the major tributary streams, namely Giran, Panzara, and Purna meet the main river from the south (Fig. 1). Cretaceous-Eocene Deccan Trap basalts and late Quaternary alluvium are the important geological formations in the basin. Downstream of Harda (Fig. 1) the Tapi River is developed into the late Quaternary alluvium. Owing to the deeply incised nature of the channel, even high flows are generally insufficient to fill the entire channel (Kale et al, 1994). Large floods, therefore, are confined within the channel banks, and spread laterally only through deeply incised bank gullies.

The Tapi River and its tributaries are monsoon fed. The average annual rainfall of the basin is 830 mm. About 90% of the annual rainfall is recorded during the monsoon months (June to October). July is the rainiest month for the basin, and accounts for nearly one-third of the annual precipitation. Flood-producing, heavy rainfall events result from invasion of cyclonic storms and depressions originating over the Bay of Bengal (Dhar and Nandargi, 1995). The highest one-day heavy rainfall within the basin ranges between 86 and 459 mm.

Annual hydrographs of the trunk stream and the tributary streams show a simple regime with only one pronounced maximum. Over 90% of the monsoon discharge is recorded in the monsoon months (June to October). Therefore, almost all the geomorphic work of erosion and sediment transportation is confined to these four to five months of monsoon season (Kale and Hire, 2004). The available gauged data further indicate that the Tapi River is characterized by one of the most intense flood regimes in the monsoonal tropics (Kale et al., 1994). The mean discharges range between 1300 and 11000 m³/s. The highest flood ever recorded on the Tapi River at Ukai in 1968 was of the order of 42,450 m³/s, which is higher than or comparable with some historical floods on large Indian Peninsula rivers, such as the Mahanadi, the Krishna and the Kaveri Rivers.

Data and Methodology

The main objective of this paper is to evaluate the geomorphic effectiveness of large floods in terms of the flow duration and stream power per unit boundary area. In order to understand the temporal variations in specific energy it is essential to first analyze the at-a-station rise and fall of water level (stage) and/or discharge during a flood event. This is achieved by analyzing the flood hydrographs.

For most gauging stations on the Tapi River and its tributaries, data regarding hourly or daily variations in discharge for major flood events are not available. However, flood hydrographs for a few major historical flood events have been published by the Central Water Commission (CWC), New Delhi and by other workers (for example, Ramana Murthy and Dev, 1980; Ramaswamy, 1985). These flood hydrographs have been used in the present study. The hydrographs are available for four river gauging sites located in the lower reach of the Tapi River, namely, Surat, Kathore, Ukai and Gidhade (Fig. 1). Two great floods on the Tapi River that were recorded in 1959 and 1968, and one relatively common, moderate-magnitude flood that occurred in 1969 were investigated. The August 1968 flood, with a magnitude of 42,450 m³/s, is the largest flood recorded on the Tapi River during the 20th Century.

Following Costa and O'Connor (1995), stream-power graphs were derived for the above-mentioned flood events. For the construction of such graphs, data regarding temporal variations in hydraulic geometry variables (flow width, depth, velocity, etc.) throughout the flood period are required. Such data were not available for the 1959 and 1968 great floods. However, flood hydrograph for 1969 flood was available for the Gidhade site on the Tapi River (peak Q = 26,665 m³/s). For the same site, hydraulic geometry equations were derived. Therefore, for this flood event, stream-power graph could be prepared. Stream power per unit boundary area was computed with the help of following formula (Baker and Costa, 1987)
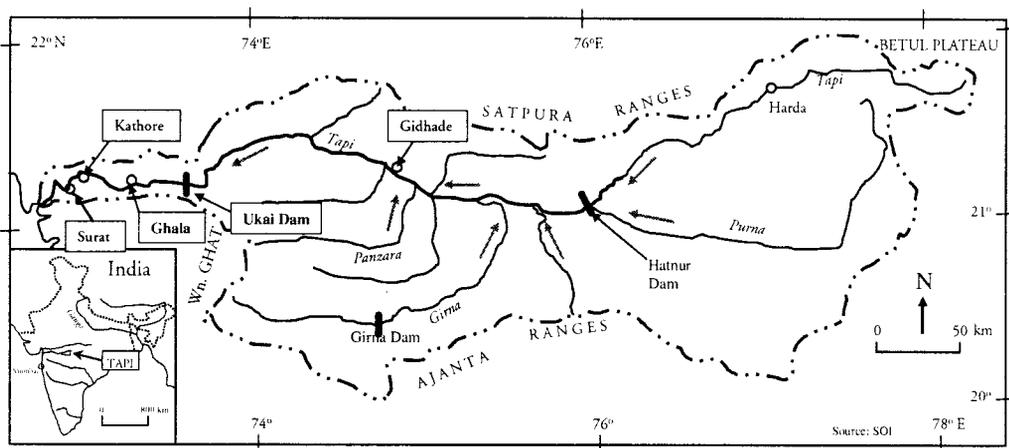

Fig.1 Map of the Tapi River Basin showing the location of major gauging sites mentioned in the text.

$$w = gQS/w \qquad .....Eq. 1$$

where, w is unit stream power expressed in watts per square meter (W/m^2), g is the specific weight of clear water (9800 N/m^2), Q is discharge in m^3/s, S is the slope, and w is the water surface width in m.

The 1959 (peak Q = 37,240 m^3/s) and 1968 (peak Q = 42,450 m^3/s) great floods on the Tapi River were extraordinary events in the last century and were capable of generating large amount of total energy and severe geomorphic impacts. Although the flood hydrographs for these two great events at Ukai (Fig. 1) have been published by Ramaswamy (1985), data regarding all the requisite hydraulic parameters for these two events are not available for this or any other gauging site on the Tapi River. Hence, an indirect method was adopted to construct the flood hydrographs for these two geomorphologically significant events at the Ghala site, located downstream of the Ukai Dam site (Fig. 1). The following procedure was adopted (Kale and Hire, 2004):

(a) The channel cross-section of the Ghala gauging site was obtained from CWC.

(b) The daily stage levels of the 1959 and 1968 flood events at the Ghala cross-section were derived using the power-law regression equation (r = 0.98) between flood stage at Ghala and flood discharge at the Ukai Dam.

(c) For different daily stage levels, the water surface width (w) and channel area of the flood were measured from the Ghala cross-section.

(d) The channel slope (S) for the Ghala reach was obtained from topographical maps.

(e) Using these data and Eq. 1 the daily unit stream power values were estimated to

understand the temporal variations in specific stream energy over the duration of the flood.

Finally, the critical unit stream power necessary to entrain cobbles and boulders has been used as a measure of the geomorphologic effectiveness of the flows (Kale and Hire, 2004). For this, the Williams' (1983) equation (w = 0.079 $dg^{1.27}$; where dg is particle diameter in mm). The minimum critical values of unit stream power that could initiate cobble and boulder movement were estimated to be about 16 and 90 W/m^2 respectively.

Results and Discussion

1. Characteristics of the flood hydrographs

A flood hydrograph is a continuous plot of instantaneous discharge with respect to time, normally obtained by means of a continuous record of stage (i.e. stage hydrograph) or discharge (i.e. discharge hydrograph) (Chow, 1964). The shape of the flood hydrograph is the result of the rainfall and basin characteristics (Petts and Foster, 1985). Fig. 2 gives the flood hydrographs of some large-magnitude flood events (1944, 1959, 1968, 1970, etc.) recorded at various gauging sites on the Tapi River. The discharge-time graphs show that the individual high flow events generally occur for about 140 to 360 hours or 6 to 15 days. This is expected in a highly elongated basin such as the Tapi Basin. The flood hydrographs, therefore, indicate that the floods on the Tapi River are long duration events. In case of all the flood hydrographs (Fig. 2) the limbs are not very steep like the hydrographs of ephemeral or highly seasonal streams, but show a gradual increase or decrease in discharge. Usually it takes a few days to reach
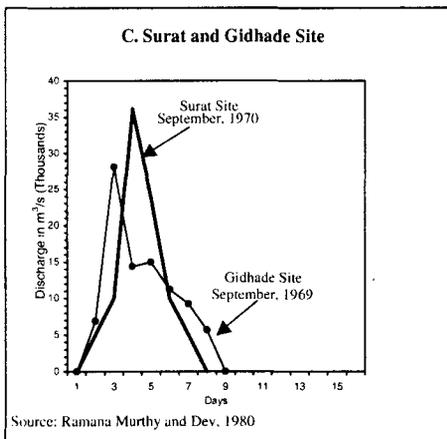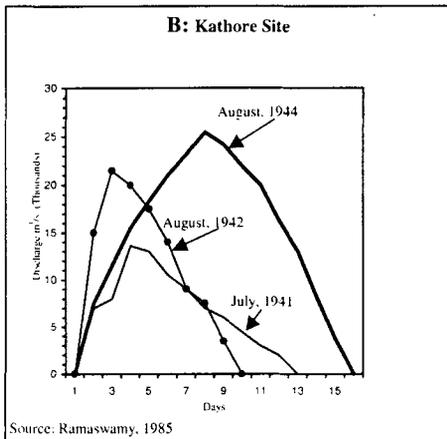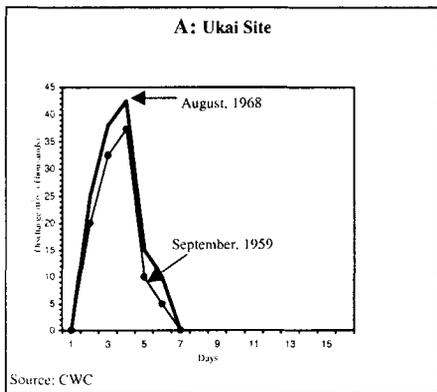
A: Ukai Site

August, 1968

September, 1959

Source: CWC

B: Kathore Site

August, 1944

August, 1942

July, 1941

Source: Ramaswamy, 1985

C. Surat and Gidhade Site

Surat Site
September, 1970

Gidhade Site
September, 1969

Source: Ramana Murthy and Dev, 1980

Fig.2 Flood hydrographs for some major flood events on the Tapi River. After Ramana Murthy and Dev (1980) and Ramaswamy (1985).

the peak discharge. For example, the hydrographs of the two most severe floods (1959 and 1968 floods, Fig. 2A) reveal that the discharge rose gradually for about 3 days before reaching the peak. The falling limbs of the flood hydrographs are relatively steeper for some events, and much gentler during other occasions (Fig. 2).

The crest segment of a flood hydrograph represents peak discharge from a drainage basin for that event. Fig. 2 shows that the crest segments of all but one flood hydrographs are short and sharp, implying that the peak flows are generally short-lived. However, unlike other large floods, the crest of the highest flood on record (1968 flood) is not sharp, but more rounded. This is to say that near-peak discharges occurred for a much longer duration during the 1968 great flood. This has important geomorphic implications.

The important points that emerge from the above discussion on the flood hydrographs are: large-magnitude floods on the Tapi River are long lasting and the peak or near-peak discharges can be sustained for longer duration during exceptionally high flood. Geomorphologically, the landform response to such high-energy, long-duration floods is likely to be significant especially in alluvial reaches in terms of bed and bank erosion, and coarse sediment transport. Long duration high-flows completely saturate alluvial channel banks, leading to the reduction in their shear strength and ultimately to their failure at peak discharge conditions. Further, because more sediment load is transported during high flows (Kale and Hire, 2004), it is most likely that tremendous amount of sediment was transported during the 1959 and 1968 severe floods.

Although flood hydrographs give a fairly good idea about the peak discharge characteristics and the duration of flood-flows, they do not provide any information regarding the peak or average flood power or about the total amount of energy expended over the duration of a flood. It is now well established that the efficacy of a flood is enhanced or reduced by the channel geometry (Kale and Hire, 2004). High flows in steep, narrow channels (low width-depth ratio) are geomorphologically more effective then in wide and shallow channels (Baker and Kale, 1998). Therefore, the flood hydrographs have to be converted into stream-power graphs by taking into account the absolute discharge as well as the channel geometry parameters, such as width, depth and slope.

2. Distribution of stream power over flood hydrographs

If flood-flow duration is considered to be a vital factor in the ability of great floods to change landforms, then it is important to know the temporal distribution of specific stream power during a flood. Peak stream power is useful in evaluating flood competence (Costa, 1983; Williams, 1983), but it is not the sole factor in assessing whether a flood may be geomorphically effective (Costa and O'Connor, 1995). Fig. 3 shows the stream-power graphs constructed for the three floods (1959, 1968 and 1969) on the Tapi River. For the 1969 flood at Gidhade, the flood power was above the threshold of cobble-movement (16 W/m^2) for more than 120 hours and above the entrainment of boulder-threshold (90 W/m^2) for about 24 hours. In comparison, during the great floods of 1959 and 1968 at Ghala, the specific
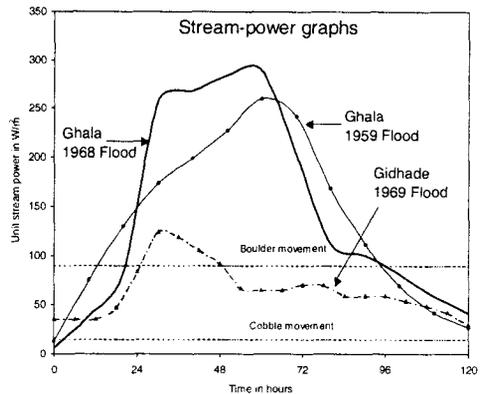

Fig. 3 Stream-power graphs of the 1959, 1968 and 1969 floods on the Tapi River. Modified from Kale and Hire (2004).

stream energy was above the threshold of cobble-movement throughout the flood period, and the boulder-threshold was exceeded for about 72 hours (about 3 days). This, therefore, clearly implies that enormous amount of coarse sediments was most likely moved during the 1959 and 1968 great floods.

Estimations further indicate that during the aforesaid flood events, the peak unit stream power values were in the range of 100-300 W/m^2. The peak value was close to 120 W/m^2 for the relatively common, moderate-magnitude flood recorded in 1969 at Gidhade site. In comparison, the peak stream power values for the 1959 and 1968 great floods at Ghala were 260 and 290 W/m^2 respectively. It is pertinent to mention here that the latter two flood events were the largest in terms of magnitude after the 1837 extreme-flood on the Tapi River (Kale and Hire, 2004). Such elevated unit stream power values are remarkably high for alluvial rivers, because great floods along large, low-gradient alluvial rivers such as the

Ganga, the Brahmaputra and the Mississippi Rivers usually have peak stream power values less than 50 W/m² (Baker and Costa, 1987; Costa and O'Connor, 1995; Kale, 2003). Therefore, the occurrence of long duration floods on the Tapi River, coupled with high stream power values are indicative of the high capability of the floods to produce significant and perhaps permanent alterations in the alluvial channel morphology.

The area under the stream-power graphs represents the total energy expended during a flood event (Costa and O'Connor, 1995). It is evident from the graphs given in Fig. 3 that the total energy generated during the common, moderate-magnitude flood in 1969 was significantly lower than the total energy produced by the great floods of 1959 and 1968. The huge floods therefore not only had higher peak unit stream power, but also significantly higher total energy. It can be, therefore, concluded that the large-magnitude floods on the Tapi River have sufficiently large energy to exceed the erosion thresholds.

Conclusions

It is evident from the above discussion that floods on the Tapi River are major hydro-geomorphic events from the standpoint of geomorphic effectiveness and work. During individual flood events, the flood peaks occur after 2-3 days from the time when discharge starts rising. In most cases, the duration of floods can range from 6 to 10 days, and in exceptional cases up to 15 days. Quantitative evaluation of the efficacy of the high-magnitude flows presented in the previous sections leads to four important conclusions regarding great floods on the Tapi

River – (a) large-magnitude floods are associated with remarkably elevated values of the unit stream power (250-300 W/m²), which are significantly higher than those estimated for large, alluvial rivers, (b) the total energy generated during great floods is several times higher than the common monsoon floods, (c) the energy levels are above the threshold of boulder transport (>90 W/m²) for several tens of hours, indicating that the flows are capable of moving very coarse sediments as bedload during such events, and (d) extraordinary floods, such the 1968 flood, not only generate abnormally high values of peak stream power per unit area, but the near-peak stream power conditions are also sustained for a longer duration. Tremendous changes in the morphology of alluvial channels are expected during such event.

The results of the analyses presented in this paper clearly indicate that large-magnitude floods are the most geomorpho-logically effective fluvial events in monsoonal rivers. Unfortunately, systematic data on the bed and bank erosion, channel changes, and coarse sediment transport are not available for the great floods that occurred about 40 to 50 years ago. However, comparison of multi-date channel cross-sections across the Tapi River have revealed noteworthy erosion and changes in the channel cross-sectional morphology by floods of much lower-magnitude then discussed in this paper. This case study of the large-magnitude floods on the Tapi River, therefore, demonstrates that great floods are undoubtedly effective geomorphic agents in monsoonal tropics.

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