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Geomorphic Effectiveness of the August 2006 Flood in the Tapi River, India

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Abstract: *Geomorphic effectiveness of the August 2006 flood in the middle and lower reaches of the Tapi river has been quantitatively assessed in this paper. Flood hydrograph available for this flood revealed that the duration of flood ranged from 10 to 11 days. The channel response to such long duration floods, particularly in alluvial sections, is geomorphologically likely to be significant in terms of bed and bank erosion as well as coarse sediment transport. Stream-power graph constructed for the event suggested a unit stream power of more than 200 W m^{-2}, which released energy several times higher than during the normal monsoon floods, and was capable of transporting large bedloads, with implications for significant modification of channel bed morphology. Consequently, the erosional potential of the river might have also increased manifold, as was attested by bank cuts of ~20m.*

Introduction

One of the major themes in modern flood geomorphology is quantitative assessment of the geomorphic effectiveness of flows of different magnitude and frequency. In the case of flood events this is generally done through measurement of the absolute magnitude of flows, the frequency at which they occur, and the amount of suspended sediment they transport (Wolman and Miller, 1960). The ability of a flood to erode the bed and bank material, transport coarse sediments and modify the landscape is commonly evaluated in terms of the stream power per unit boundary area or the boundary shear stress (Costa, 1983; Baker and Costa, 1987), as well as the flood flow duration (Costa and O'Connor, 1995), rather than absolute flood magnitude alone. Striking contrasts in river response to large floods could be attributed to the duration of events and their hydraulic characteristics, which could be better understood from stream-power graphs, as constructed from the discharge rating curves, channel geometry, and flood hydrographs (Costa and O'Connor, 1995).

Floods, especially the large ones, play a dynamic role in shaping the landscape in the monsoonal tropics, although they are infrequent over space and time (Wohl, 1992; Gupta, 1995; Kale, 2003, 2007, 2008; Kale and

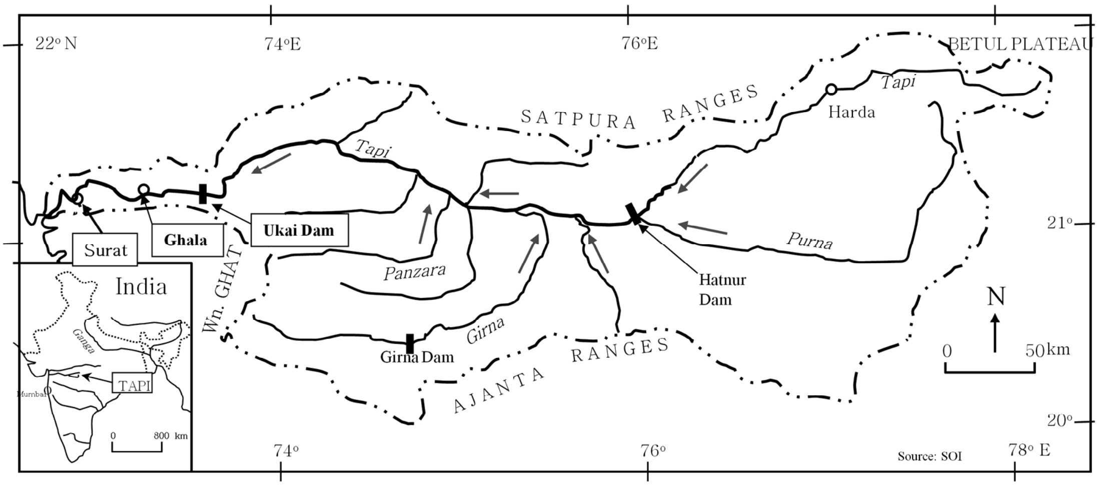

Figure 1. Map of Tapi river basin showing the location of Ghala gauging site and other locations mentioned in the text

Hire, 2004). Therefore, a major theme of many recent investigations has been the determination of the effectiveness of those large floods (Baker and Costa, 1987; O'Connor and Baker, 1992; O'Connor, 1993; Costa and O'Connor, 1995; Benito, 1997; Kale, 2003, 2007, 2008; Herget, 2004; Miller, 1990). Several studies have shown that the large magnitude floods that occur at an interval of several decades, are associated with much higher levels of power expenditure than is achieved during the normal floods, which result in major channel morphological changes and movement of coarse sediments (Gupta, 1995; Baker and Kale, 1998; Kale, 2003, 2007, 2008; Herget, 2004; Kale and Hire, 2004, 2007; Hire and Kale, 2006). However, there is a general paucity of studies to quantitatively evaluate the geomorphic effect of large-magnitude floods on monsoonal rivers. The objective of this paper is to quantitatively examine the geomorphic work in the monsoonal Tapi river of central India during a large-magnitude flood in August 2006.

Geomorphic and hydrological setting of the Tapi basin

The Tapi river is the sixth largest river in the Indian Peninsula with a catchment area of 65145 km^2. It has an elongated drainage basin with a structurally-controlled drainage network (Fig. 1). Most of the higher order tributaries like Purna, Girna, and Panzara, meet the Tapi from the south. Deccan Trap basalts (Cretaceous-Eocene) and late Quaternary alluvium are the major geological formations in the basin. The middle and lower parts of the basin are covered by thick late Pleistocene alluvium. Upstream of Harda, the channel of the Tapi river is incised in the bedrock, whereas downstream of Harda, it is incised in the late Pleistocene alluvium (Fig. 1). Owing to the deeply incised nature of the channel even the high flows are generally insufficient to fill the entire channel (Kale *et al.*, 1994). Large floods are, therefore, confined within the channel banks, and spread laterally only through incised bank gullies.

The basin has an average annual rainfall of 814 mm, more than 90% of which is received during June-October (the wet season). July is the rainiest month when nearly one-third of the rain is received. Flood-producing, heavy rainfall events are usually associated with occasional cyclonic storms from the Bay of Bengal (Dhar and Nandargi, 1995). The rainstorms are generally of 1 to 2 days' duration and the maximum 24-hour heavy rainfall ranges from 86 to 459 mm (Abbi and Jain, 1971).

Annual hydrographs of the Tapi river demonstrate a simple regime with only one distinct peak during the wet season, when almost all the geomorphic work of erosion and sediment transportation take place (Kale and Hire, 2004). The available gauged data also suggest that the Tapi River is characterised by one of the most intense flood regimes in the monsoonal tropics (Kale *et al*., 1994). The maximum peak flood recorded so far was 42,450 $m^3 s^{-1}$ in 1968 at Ukai, which is higher than or comparable to some of the historical large floods in the Krishna, Kaveri and Mahanadi. The peak unit discharge of the river is 0.65 $m^3 s^{-1} km^{-2}$. Two other mega–floods in the Tapi River were recorded during 1959 and 1968.

Data and methodology

Data of hourly or daily discharge and/or stage for major flood events are not available for most gauging stations on the Tapi River and its tributaries. Notable exceptions are the hydrographs for the 1959, 1968 and 1969 flood events at Ukai, which were analysed by Hire and Kale (2006).

For this study, a stage flood hydrograph of the August 2006 flood for Ghala (a site in the lower reaches of the Tapi) has been used, which is available with the Central Water Commission (CWC), New Delhi. The August 2006 flood was one of the large-magnitude floods (peak discharge 27,152 $m^3 s^{-1}$) in the lower reaches of the Tapi River. Although the stage flood hydrograph for this event at Ghala was available, data on other relevant hydraulic parameters were not. The peak water level (stage) and corresponding discharge data, available for 19 annual peak floods at Ghala were, therefore, used to construct the discharge-flood hydrograph. In order to establish relationship between peak water level (stage) and corresponding discharge for the 19 annual peak floods, 25 regression equations were applied to the data. A quadratic regression equation (explained variance 99.9%) was found to be the most suitable. Using the quadratic regression equation, hourly discharges of the 2006 flood were derived. The water surface widths (w) of the flood were measured from the Ghala cross-section. Topographical maps were used to obtain the channel slope (s) at Ghala.

Following formula was applied to calculate stream power per unit boundary area (Baker and Costa, 1987):

$$\omega = \gamma QS/w \qquad \text{.....Eq. 1}$$

where, w is unit stream power expressed in watts per square meter (Wm^{-2}), γ is the specific weight of clear water (9800 Nm^{-2}), Q is discharge in $m^3 s^{-1}$, S is the slope, w is the water surface width in m.

The critical unit stream power per boundary area necessary to entrain cobbles and boulders was applied to find out the geomorphic effectiveness of the flood (Kale and Hire, 2004; Hire and Kale, 2006). This was done using the Williams' (1983) equation:

$$\omega = 0.079\ dg^{1.27} \qquad \text{.......Eq. 2}$$

where, dg is the particle diameter in mm. It was estimated that a minimum of 16 Wm^{-2} unit stream power was necessary to move the cobbles, while 90 Wm^{-2} was necessary to move boulders.

Results and discussion

A flood hydrograph is a continuous plot of instantaneous discharge with respect to time, normally obtained by means of a continuous record of stage (stage hydrograph) or discharge (discharge hydrograph) (Chow, 1964). The rainfall and basin characteristics determine the shape of a flood hydrograph (Petts and Foster, 1985). The flood hydrograph at Ghala reveals that the high flow event continued for more than 240 hours (i.e., >10 days; Fig. 2). The elongated shape of the basin was a major cause for such protracted flood hydrograph. The previously studied flood hydrographs of the river were also found to be of protracted nature (Hire and Kale, 2006). The rising and falling limbs of the August 2006 flood hydrograph were not very steep like the hydrographs of ephemeral or highly seasonal streams;rather it revealed a gradual rise and fall in the flow (Fig. 2). The rising limb touched the peak discharge at about one and half day from the commencement of flood. The falling limb showed two sharp peaks, which could be attributed to the release of water from the Ukai Dam (Fig. 1). Otherwise, the falling limb showed a gradual decline (Fig. 2). The crest segment of the flood hydrograph is relatively long and rounded, implying a protracted peak flow during the flood event. Such near-peak discharge has significant geomorphic implications.

Arguing on the basis of the basin shape that the Tapi river is subjected to protracted high-magnitude floods and a prolonged peak or near-peak-discharge, it may be logical to expect significant impact of such high and prolonged discharges on the alluvial channel morphology and mobility of coarse sediments, as reported by Costa and O'Connor (1995). Long duration high-magnitude flows completely saturate the alluvial channel banks, leading to reduction in their shear strength and ultimately to their failure at peak discharge conditions (Kale and Hire, 2004; Hire and Kale, 2006). Time-series analysis of channel cross-sections of the river in its alluvial reach indicate that floods of lower magnitude (Q = 18,000–19,000 $m^3 s^{-1}$) were responsible for channel erosion, and that the large floods could transport up to 70% of the annual suspended sediment load (Kale and Hire, 2004). It is, therefore, possible that the 2006 flood (Q = 27,152 $m^3 s^{-1}$) was capable of substantial bank erosion, channel modification and transportation of coarse and fine sediments.

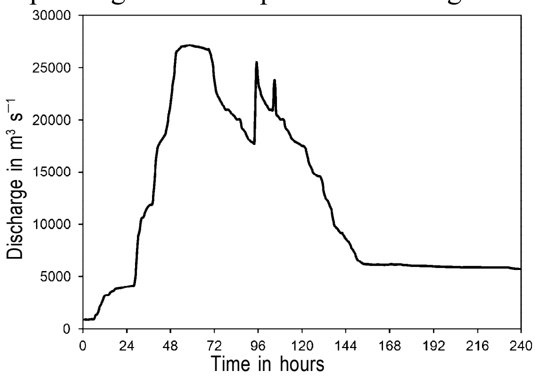

Figure 2. Flood hydrograph of Tapi river at Ghala, August 2006 (Data source: Central Water Commission)

Although flood hydrograph provides a fairly good idea about the peak discharge characteristics and duration of the flood-flow, it does not provide information on the peak or average stream power or the total amount of energy expended over the duration of a flood. Because of the stream power variation, high flows in deep, narrow channels (low form ratio) and in steeper reaches are geomorphologically more effective than in wide, shallow channels (high form ratio) (Baker and Kale, 1998; Kale and Hire, 2004; Kale, 2007; Kale and Hire, 2007). It is, therefore, necessary to convert the flood hydrograph into stream-power.

Temporal distribution of stream power during the flood

The temporal variation in unit stream power at Ghala during the August 2006 flood was calculated using Eq.1, which revealed that the maximum (peak) unit stream power was around 200 Wm^{-2} (Fig. 3). Such stream power values are remarkably high for alluvial rivers

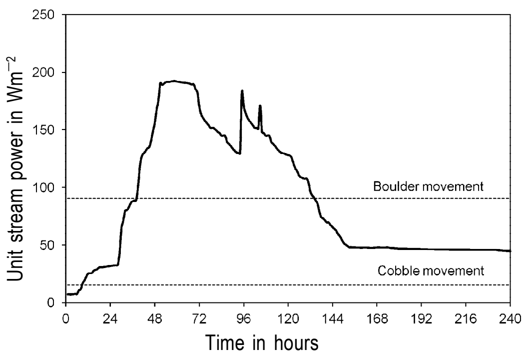

Figure 3. Sream-power graph of Tapi river at Ghala, August 2006 flood (Data source: Central Water Commission)

because large magnitude floods along large, low-gradient alluvial rivers such as the Ganga, Brahmaputra, Mississippi or the Amazon usually have peak stream power values less than 50 Wm^{-2} (Baker and Costa, 1987; Costa and O'Connor, 1995; Kale, 2003). Kale and Hire (2006) have shown that peak stream power values for the 1959 and 1968 floods in the Tapi River at Ghala were 260 and 290 Wm^{-2} respectively. Such stream power values are; however, lower by 1–3 orders of magnitude than those obtained for bedrock rivers (Baker and Costa, 1987; Baker and Kale, 1998; Kale, 2003; Kale and Hire, 2007).

The long-duration floods in the Tapi river, coupled with high stream power values indicate high capability of the floods to produce significant alterations in the alluvial channel morphology. Much higher stream power above the threshold of cobble-movement (16 Wm^{-2}) for more than 240 hours (>10 days) and above the threshold of boulder entrainment (90 Wm^{-2}) for about 100 hours (more than 4 days) suggests that substantial amount of coarse sediments were moved during the August 2006 flood. It is also likely that the river performed other significant geomorphic works during the August 2006 flood. Although in the absence of systematic data those works could not be evaluated, a field survey after the flood revealed bank erosion of ~20m in the immediate downstream of the Ukai Dam. Previous studies showed that the 1978 and 1979 floods in the middle reaches of the Tapi River transported about 20–25% of the annual suspended load, and a bank erosion of ~15 m (Hire, 2000; Kale and Hire, 2004), although the flood discharge was smaller than in 2006. It can, therefore, be concluded that the floods in the Tapi river have sufficiently large energy to exceed the erosion thresholds.

Conclusions

An analysis of the hydrograph of August 2006 flood event recorded at Ghala gauging site on the Tapi River revealed that the high flow event occurred for more than 240 hours, when the unit stream power increased to 200 Wm^{-2}. This is much higher than the power estimated for large, alluvial rivers of the world. The total energy generated during the event was several times higher than the normal monsoon floods. Since the stream power values were above the threshold for boulder movement (>90 Wm^{-2}) for several tens of hours, it also suggests that such large floodsin the Tapi river can transport significant amount of coarse sediment as bed load. Bank erosion of ~20m below the Ukai Dam suggests a very high erosion potential of the river during such high floods.

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References

Abbi, S.D.S. and Jain, B.C. (1971) A study of major rainstorms of Tapi basin for evaluation of design storm. *Indian Journal of Meteorology and Geophysics*,22: 203–212.

Baker, V.R. and Costa, J.E. (1987) Flood power. In Mayer, L. and Nash, D. (eds) *Catastrophic Flooding*, Allen and Unwin, London: 1–21.

Baker, V.R. and Kale, V.S. (1998) The role of extreme floods in shaping bedrock channels. InTinkler, K.J. and Wohl, E.E. (eds) *River over Rock: Fluvial Process in Bedrock Channels*. American Geophysical Union, Monograph, 107:153–165.

Benito, G. (1997). Energy expenditure and geomorphic work of cataclysmic Missoula flooding in the Columbia River gorge, USA. *Earth Surface Processes and Landforms*. 22: 457–472.

Chow, V.T. (1964*) Handbook of Applied Hydrology*. McGraw-Hill, New York.1495p.

Costa, J.E. (1983) Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the

Colorado Front Range. *Geological Society of American Bulletin,* 94: 986–1004.

Costa, J.E. and O'Connor, J.E. (1995) Geomorphically effective foods. In Costa, J.E., Miller, A.J., Potter, K.W. and Willcock P.R. (eds) *Natural and Anthropogenic Influences in Fluvial Geomorphology*. Geophysical Monograph, American Geophysical Union, Washington, D.C. 89: 45–56.

Dhar, O.N. and Nandargi, S. (1995) On some characteristics of sever rainstorms of India. *Theoretical and Applied Climatology*, 50: 205–212.

Gupta, A. (1995) Magnitude, frequency, and special factors affecting channel form and processes in the seasonal tropics. In Costa, J.E., Miller, A. J., Potter, K.W. and Willcock P.R. (eds) *Natural and Anthropogenic influences in the Fluvial Geomorphology.* American Geophysical Union, Monograph, 89: 125–136.

Herget, J. (2004). Reconstruction of ice-dammed lake outburst floods in the Altai Mountains, Siberia- a review. *Journal of the Geological Society of India*, 64: 561–574.

Hire, P.S. (2000) *Geomorphic and Hydrologic Studies of Floods in the Tapi Basin.* Unpublished PhD thesis, University of Pune, Pune: 192 p.

Hire, P.S. and Kale, V.S. (2006) Geomorphic effectiveness of high-magnitude floods on the Tapi River: Evaluation based on flood hydrographs and stream-power graphs. *Transactions, Institute of Indian Geographers*, 28 (2): 175–182.

Kale, V.S. (2003) Geomorphic effects of monsoon floods on Indian rivers. *Natural Hazards,* 28: 65–84.

Kale, V.S. (2007) Geomorphic effectiveness of extraordinary floods on three large rivers of the Indian Peninsula. *Geomorphology,* 85: 306–316.

Kale, V.S. (2008) A half-a-century record of annual energy expenditure and geomorphic effectiveness of the monsoon-fed Narmada river, central India. *Catena*, 75(2): 154–163.

Kale, V.S. and Hire, P.S. (2004) Effectiveness of large monsoon floods on the Tapi river, India: role of channel geometry and hydrologic regime. *Geomorphology,* 57: 275–291.

Kale, V.S. and Hire, P.S. (2007) Temporal variations in the specific steam power and total energy expenditure of a monsoonal river: The Tapi river, India. *Geomorphology,* 92: 134–146.

Kale, V.S., Ely, L.L., Enzel, Y. and Baker, V.R. (1994) Geomorphic and hydrologic aspects of monsoon floods on the Narmada and Tapi rivers in central India. *Geomorphology,* 10:157–168.

Miller, A.J. (1990) Flood hydrology and geomorphic effectiveness in the central Appalachians. *Earth Surface Processes and Landforms,*15 (2): 119–134.

O'Connor, J.E., (1993) Hydrology, Hydraulics, and Geomorphology of the Bonneville Flood. *Geological Society of America Special Paper,* 274: 82 p.

O'Connor, J.E. and Baker, V.R. (1992) Peak discharges from glacial lake Missoula. *Geological Society of American Bulletin*, 104: 267–279.

Petts, G.E. and Foster, I. (1985) *Rivers and Landscape*. Edward Arnold, London: 274p.

Williams, G.P. (1983) Paleohydrological methods and some examples from Swedish fluvial environments. I. Cobble and boulder deposits. *Geografiska Annaler,* 65(A): 227–243.

Wohl, E.E. (1992) Gradient irregularity in the Herbert gorge of northeastern Australia. *Earth Surface Processes and Landforms*, 17: 69–84.

Wolman, M.G. and Miller, J.P. (1960) Magnitude and frequency of forces in geomorphic process. *Journal of Geology,* 68: 54–74.

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