Fluvial Palaeohydrological Studies in Western India: A Synthesis

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Abstract

The river basins of India are important repository of the late Quaternary hydrological and climatic changes. The long term (millennial scale) and short term (centennial scale) hydrological changes in these river basins can be reconstructed through the records of planform alterations and sediment deposits that occur during the rare extreme flood events. The status of fluvial palaeohydrological studies in western India and the future prospects are discussed in this synthesis. Almost continuous palaeoflood records spanning two thousand years is available from the bedrock rivers on western India, whereas older events dating back to ~ 5 ka have also been documented from the alluvial reaches. Though bedrock gorges are considered to be ideal sites for the preservation of palaeoflood deposits and related discharge estimations, the alluvial reaches of the rivers in western India owing to their unique geomorphic setup are equally promising. Regime-based palaeodischarge estimations for the average flows in these alluvial reaches would be significant in providing a regional history of the hydrological changes that have occurred in the river basins of western India.

Introduction

The fluvial hydrologic regime is sensitive to climate change and the system responds by altering its morphology and sedimentation pattern. Palaeohydrological studies are thus significant in deciphering climatic changes. The fluvial deposits preserved in the overbank sites are largely the records of flood events and detailed studies of such deposits provide information on the flood frequency, character and flood magnitude. The channel planform alterations on the other hand, indicate the changing average flow regime in the fluvial system. In India, where the hydrological records are extremely short, the value of historical and palaeohydrological data is substantial. Palaeoflood investigations in some of the Indian rivers, namely, Narmada (Ely et al., 1996; Kale et al., 1997, 2003), Tapi (Kale, 1999), Godavari, Krishna and Pennar (Kale et al., 1996), Luni (Kale et al., 2000) and Mahi (Alpa, 2007a,b) have been carried out and the slackwater records, augmented by gauge and historical records indicate significant changes in the frequency and magnitude of large floods during the last two thousand years. All rivers studied barring Luni and Mahi are known for their spectacular monsoon discharges and occur in the sub-humid to humid climatic zones and most of these palaeoflood sites have been located in the bed rock gorges. The status of fluvial palaeohydrological studies in western India and the future prospects is discussed here.

Palaeohydrological Studies: the Concept

Palaeohydrological interpretations are concerned with the reconstruction of former river flows, be they average flows of low to moderate magnitude and frequency, or infrequent high magnitude events. The latter are commonly reconstructed in the bedrock settings using slackwater deposits and other palaeostage indicators (Baker, 1987), whereas
the discharge estimations of average flows is based on the palaeochannel dimensions and sedimentological characteristics in the alluvial reaches (Patton, 1988; Reinfelds, 1995). The most commonly used techniques in palaeohydrological investigations include palaeostage estimates and regime-based palaeoflood estimates (Baker, 2000). The palaeostages can be estimated by documenting flood-induced erosion or deposition up to the water level reached by a flow. The slackwater deposits and palaeostage indicators occurring along stable-boundary fluvial reaches are the best preserved records of palaeoflows. Unconsolidated sands and silts that accumulate relatively rapidly from suspension during major floods, particularly where flow boundaries result in markedly reduced local flow velocities are described as slackwater deposits (Baker, 1987). For palaeoflood studies, a slackwater sedimentation site should be optimum for both the accumulation and preservation of the relatively fine-grained sediments carried high in flood flows at maximum stage. A few ideal sites of deposition and subsequent preservation of slackwater deposits have been described (Kochel and Baker, 1982; Baker, 1987; Benito et al., 2003b); amongst these the most common are the tributary mouths, channel-margin alcoves, caves and rock shelter deposits. The local hydraulic conditions at these sites result into a drop in the flow velocity and deposit flood sediments. Therefore, most palaeoflood studies are concentrated along the bedrock reaches of the rivers. Stratigraphical, sedimentological and chronological studies of the slackwater deposits provide reasonably accurate information about palaeofloods – their timing and magnitude. The palaeoflood deposits can be dated using radiocarbon or optically simulated luminescence dating. The palaeoflood magnitudes are determined by comparing the palaeostage indicator levels with water surface profiles generated by step-backwater computer program (O'Connor and Webb, 1988). The regime-based palaeoflood estimation procedures use empirically derived relationships to relate high-probability flows to palaeochannel dimensions, sediment types and other geomorphic expressions. The relations apply in particular to alluvial channels which adjust their planform to high flood discharges. The Indian River systems, thus, promise ample scope for the alluvial as well as bedrock palaeohydrological investigations; however, so far most of the studies remained focused on the palaeoflood estimations.

Palaeoflood records in western India

The western Indian region discussed here includes the southern Thar Desert, the Alluvial Plains of Gujarat and a part of Deccan Peninsula. The rivers Luni, Sabarmati, Mahi, Narmada and Tapi flowing through the southern Thar Desert and the Gujarat Alluvial Plains originate in the Aravalli and Vindhyan ranges and flow westward into the Arabian sea, whereas the rivers Godavari and Krishna arising in the Deccan Peninsula flow eastward into the Bay of Bengal (Fig.1). Palaeoflood records are available from the bedrock reaches of the Krishna, Godavari, Tapi, Narmada, Mahi and Luni rivers and from alluvial reaches of Mahi and Narmada (Fig.1).

Narmada is the most studied river basin for its palaeoflood record owing to its intense flood regime. Almost a 2000- year record of large floods has been assembled in the bedrock gorges of Narmada river basin (Kale et al., 2003). The oldest record of catastrophic floods in the Narmada several millennia before the Last Glacial Maximum is the coarse gravel layer 7m above the bed of the palaeochannel at Bhedaghat (Rajaguru et al., 1995). A record of the mid Holocene floods is documented at Barjar in the Choral River, a tributary of Narmada. About seven flood units have been identified and the lowest unit has been dated to 5170±135 years BP indicating that half-a-dozen large floods have occurred on the Choral River during the last 5 ka (Kale et al., 1993). Continuous sequences of late Holocene floods have also been documented along the main river at Punasa (Kale et al., 1994, Ely et al., 1996) and Sakarghat (Kale et al., 1997). The slackwater deposit sequence at Punasa is dominated by multiple flood units of sands and clays and has preserved an evidence of at least 14 floods that have occurred during the last 1700 years. The sequence at Sakarghat (Fig. 2) comprises about 26 flood units that have been grouped into four distinct series and spanning over 2000 years. Kale et al., 2003 have inferred from the total palaeoflood record of the Narmada River that a number of extraordinary floods occurred during 400-1000 AD and post-1950 AD and that floods of lower magnitude and frequency generally characterized the period 1400-1950 AD.

The Tapi River, also known to have a history of extreme floods, has preserved palaeoflood records in its bedrock gorges. The older flood deposits have been located at Guttigarh (Kale et al., 1994) comprising a 4m thick sequence of silty clay sediments. A radiocarbon date of the shells occurring about 2m below the surface is about 8510±100 years BP in age. Late Holocene flood events have also been documented at Guttigarh, Teska and Khapa. At Guttigarh the upper units have yielded post-1950 radiocarbon dates (Fig.3) and the bottom most units a maximum age of 240± 50 years BP. Kale et al. (1994) have also suggested based on the hydraulic modeling that the highest flood deposits at this site were associated with floods close to 4000m³s⁻¹. The 2m thick sequence at Teska contains evidence of 6-9 floods and the oldest event has been dated back to 225±40 years BP. At Khapa, the 2.5 m thick section reveals the presence of 13 flood units emplaced by floods later than 380±45 years BP (Kale et al., 1994).
Slackwater deposits in the alluvial reaches of the Mahi River occur in the ravines incised during the early Holocene on an alluvial surface comprising sediments of Late Pleistocene age (Alpa, 2007a). The slackwater deposits occur at elevations up to 20 m from the present river level and extend to about 500 m inland. The carbonate rich sediments forming the ravine cliffs have provided bank stability and the dissections in the ravines have helped in the accumulation of slackwater deposits due to backflooding of the floodwater from the main channel. Recent gullies have incised the sediments and exposed deposits related to major flood events. The best exposures of slackwater deposits have been observed at Dodka (Fig.3). The sediment succession of the slackwater deposits is dominated by bedsets and laminasets of silt and sand separated by colluvial sediments. Four events of flood deposition occurred during the mid to late Holocene. Two units of slackwater deposits, SWD 2 and 4 have been dated by IRSL at 4.6 ± 1 ka and 1.7 ± 0.5 ka (Alpa, 2007a). The stratigraphy of these deposits indicates that the first two slackwater units (SWD1 and SWD2) have resulted due to flooding in a regime of intense monsoon. The other two units, however, represent extreme high magnitude floods in a period of low average precipitation.

Regime based palaeoflood estimation has also been attempted in the alluvial reach of the arid Mahi River basin to quantify contemporary and palaeo-discharges and changes in the hydrologic regime through the mid-late Holocene (Alpa, 2007b). The occurrence of terraces and pointbars high above active river levels (Fig. 4) and change in the width/depth ratio can be regarded as geomorphic responses to changes in discharge. Discharge estimates are made based on the channel dimensions and established empirical relations for the mid-late Holocene, historic (the channel that deposited extensive pointbars above the mid-late Holocene channel was ~55 000 m³s⁻¹ and that of the historic channel was ~9 500 m³s⁻¹, some ~25 times and ~5 times greater than that of the present river (2000 m³s⁻¹), respectively.
Fig.3. Lithologs of slackwater deposits at Guttigarh on Tapi River (Kale et al., 1994), at Dodka in the alluvial reach of Mahi River (Alpa, 2007a) and at Bhuka in the Sindari gorge on Luni River (Kale et al., 2000)

The ephemeral Luni River flows through the Thar Desert of India and has been catastrophically flooded in the recent past. Evidences of such extreme events in the past have been recorded in the slackwater deposits preserved in the back-flooded tributary at Bhuka (Kale et al., 2000). The study suggests that the Luni River has experienced at least 17 extreme floods during the past millennium. The hydraulic modeling carried out for the top most flood units indicate the related peak discharges to be close to 12 000 m³ s⁻¹ (Kale et al., 2000).

Palaeoflood records spanning almost 2000 years have been documented from the Krishna and Godavari rivers by Kale et al. (1996). The slackwater deposit sequences in the upper Krishna basin have preserved eighteenth century pottery. Similarly, radiocarbon dates from Annapur (770±80 years BP) and Bibi (180±90 years BP) represent high magnitude floods in the upper Krishna basin. At Manjri, human skeletons have been discovered below 8m flood deposits of about 4000 years in age. High magnitude floods in the Chalcolithic period ~ 3000 years BP have been reported at Daimabad in the upper reaches of the Godavari River (Rajaguru, 1986).

**Palaeodischarge Estimations**

Estimation of discharges associated with extreme events is based on the elevations of the slackwater deposits or other stage indicators and step-backwater modeling is performed to generate related water surface profiles. Palaeodischarge calculations have been carried out at a few select sites in the Narmada, Tapi, Luni and Mahi rivers using HEC-
2 computer program. The highest slackwater deposits at Sakarghat in the Narmada basin post-1900 are associated with discharges between 55 000 and 60 000 m$^3$s$^{-1}$ and at Barjar in Choral river, a tributary of Narmada are found to be associated with discharges >4 500 m$^3$s$^{-1}$ (Kale et al., 1992, 1994). Similar estimation carried out at Guttigarh on Tapi river suggests that the highest flood deposits here probably post-1950 can be related to floods close to 4 000 m$^3$s$^{-1}$. The estimation of peak discharges using similar techniques has been attempted by Kale et al. (2000) in the Luni River and the results indicate peak discharges closer to 12 000 m$^3$s$^{-1}$. The peak discharge associated with the highest slackwater deposits dated to 1.7 ka at Dodka in the Mahi basin has been estimated to be around 55 000 m$^3$s$^{-1}$ (Alpa, 2007a). Estimations on average flow discharges in the alluvial Mahi River have also been attempted by Alpa (2007b) and these are based on the channel dimensions and established empirical relations. Accordingly bankfull discharges for the Mahi river channel during three distinct time periods viz. mid-late Holocene, historic and present have been calculated to ~ 55 000 m$^3$s$^{-1}$, 9 500 m$^3$s$^{-1}$ and 2 000 m$^3$s$^{-1}$ respectively.

![Fig.3](image)

**Fig.3.** Section across the Mahi River exhibiting the channel dimensions and bankfull stages during the mid-late Holocene, historic time and present day (Alpa, 2007b).

**Discussion**

All the major Indian rivers are rain fed and monsoon related storms are the major cause of high magnitude floods in the modern period. The most well documented and continuous palaeoflood records related to these extreme events span about 2000 years. The detailed analysis of these records on the humid to sub-humid Narmada, Tapi, Krishna and Godavari show clustering of events in certain time periods. According to Ely et al. (1996), a major break in the flood frequency occurred between ca. 400 to 0 $^{14}$C years BP. There is also evidence of clustering of low frequency, extreme floods between 400 and 1000 AD and post-1950. The palaeoflood record spanning 800 years in the Luni River also show similar
clustering between 1000 and 500 years of high floods and was followed by a period of reduced floods (Kale et al., 2000) corresponding to the Medieval Warming and Little Ice Age epochs respectively.

The slackwater deposits of the post-1950 flood events are found to rest over the older units in these river basins suggesting a higher magnitude of modern floods. Kale et al. (2000) also suggest that the post-1950 floods were the largest during the historical period while the early Holocene floods were the largest at least in the Holocene on the Narmada River. The palaeoflood records, as located so far, on the semi-arid Mahi River however, do not confirm to this fact. Whereas the older flood deposits are located in the ravines further away from the main channel, the historic and modern floods appear to have been deposited in the proximity to the main channel. However, the study is still incipient and needs further confirmation of ages for the recent flood sediments. The alluvial reach of the Mahi River has in fact preserved a spectacular record of mid-late Holocene flood events dating back to about 5000 yrs as compared to those in the bedrock gorges. Similar record dating back to ~8000 yr BP in Tapi and 5170 yr BP in Choral River has been reported.

The palaeoflood records available in the western India and discussed here suggest distinct linkages between individual river basins. The palaeoflood history for the past 5000 years in the Narmada, Tapi, Mahi, Luni, Krishna and Godavari rivers appears to be broadly comparable. A review by Kale (2008) also suggests that changes in the flood regime conditions of most of the Indian rivers are linked to fluctuations in the monsoon intensity and the associated phenomena on different timescales. Qualitative data on the hydrological changes in the various river basins is available in terms of the palaeoflood records however, quantification of discharge variance is lacking. A few quantitative estimations of peak discharges though available do not even help in subtle inferences as they are not very time specific. The available palaeodischarge estimates have been used to develop a regional flood envelop curves for the Indian Peninsula (Kale, 2008). The curves suggest that the largest palaeofloods were lower than the modern (post-1950) extreme floods.

Palaeoflood hydrology and palaeodischarge quantification provides information on the extreme flood events for the gauged and ungauged rivers and extends the records of largest floods.

Palaeohydrological studies, therefore, have lot of relevance for the river systems of India where the available gauge records are very short. Also, most of the lower order streams are ungauged and have lot of bearing on the hydrologic regime of the river. Palaeohydrological studies in the Indian rivers over the last two decades have shown immense scope for further palaeoflood analysis. Although the potential for palaeoflood studies in alluvial rivers is limited, it has been possible to reconstruct the palaeoflood history of the Mahi River due to its peculiar geomorphic setting (Alpa, 2007a). Almost all the major rivers of the Gujarat Alluvial Plains offer similar boundary conditions and hence, can be extensively explored for palaeoflood reconstructions. It would also be interesting to carry out discharge estimates for the average and bankfull flows of these alluvial rivers during distinct time periods using the unique geomorphic indicators. Such estimates along with the ones of extreme events from the bedrock reaches of Peninsular rivers would provide a regional picture of the hydrological variations that have occurred in western India and their possible links to climate change.
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