Sedimentary records of palaeofloods in the bedrock gorges of the Tapi and Narmada rivers, central India

Vishwas S. Kale*,†, Sheila Mishra and Victor R. Baker§**

†Department of Geography, University of Pune, Pune 411 007, India
**Department of Archaeology, Deccan College, Pune 411 006, India
§Department of Hydrology and Water Resources, University of Arizona, Tucson AZ 85721, USA

High-magnitude floods are an integral part of the hydrologic systems of the Tapi and Narmada rivers of central India. To establish whether the largest flood in 1970 on Narmada and in 1968 on Tapi had precedence in the geological records, geomorphic studies were undertaken. The main type of palaeoflood evidence is slackwater deposits in bedrock gorges. We have been able to assemble a 2000-year chronology of large floods on Narmada and a < 500-year chronology of floods on Tapi. Evidences of a large late Pleistocene flood on Narmada and early Holocene floods on Tapi have also been identified. Palaeoflood analysis indicates noteworthy clustering of flood events and a discernable link between palaeofloods and Holocene climatic changes.

THE southwest monsoon overwhelmingly dominates the rainfall supply of the Tapi and Narmada basins, producing over 90% of the total annual rainfall. As a result, the annual flow pattern of these two rivers is intimately tied to the monsoon system of climate. Commonly, cyclonic systems embedded within the monsoon system produce heavy rainfall over the basins and floods on the rivers[1]. Because the streamflow pattern of these rivers changes strictly in accordance with the monsoon rainfall, any record of modern floods, historical floods, or palaeofloods provides information about monsoon conditions. The magnitude/stage and frequency of such large floods is precisely known for the period of gauge and historical record, or approximately 100–150 years. Over the last ca. 150 years the Narmada and Tapi rivers have been subjected to high-magnitude floods on several occasions[1]. However, the information on earlier floods is lacking. Records of ancient or palaeofloods will, not only contribute to the knowledge of palaeoclimate and palaeofluvial geomorphology, but will also be useful in flood forecasting. The reconstruction of palaeofloods as generated by monsoon conditions during the late Pleistocene and Holocene is the focus of this paper.

*For correspondence. (e-mail: vskale@unipune.ernet.in)

The study areas

With a catchment area of 65,145 km^2 and 98,796 km^2 respectively, the Tapi and Narmada rivers are the two largest west-flowing rivers in India. The basins lie in a geomorphologically and tectonically active region, with frequent heavy flood-producing storms[1]. Large floods are common and the channels display a strong control of catastrophic fluvial processes. Historically, the large-magnitude floods that have rolled through the rivers have reached peaks of 42,000 to 69,000 m^3 s^{-1}. The primary cause of large-magnitude floods is tropical storms originating over the Bay of Bengal.

The river channels are deeply incised (w/d ratio 11–59)[1] in bedrock or Quaternary alluvium. Bedrock consists of Cretaceous–Eocene Deccan Trap basalts in the Tapi Basin and Proterozoic rocks of the Vindhyan Supergroup or Trap basalts in the Narmada Basin. The channel geometry demonstrates excess of flow energy and high sediment–transport capacity to sediment–supply ratio[1,2].

Scablands and prominent boulder berms are common along rocky channels[1]. These distinctive geomorphic features provide evidence of large floods, high flow velocities and elevated power per unit area in recent times[3]. Throughout their length, the incised channels exhibit a channel-in-channel topography with a low flow channel and patches of flood plain enclosed between high alluvial or rocky banks[4].

Large flood events that have occurred during the last century or so on the Tapi and Narmada rivers were synchronous, even though the relative magnitudes were different[1]. This coincidence of flood events is not surprising because the Narmada and the Tapi basins have comparable basin morphology and are affected by the same flood-generating meteorological conditions, viz. Bay of Bengal depressions and cyclones. Therefore, the flood record in one basin can be used to broadly reconstruct the long-term flood chronology of the other basin.

Historical records of floods

Within the Tapi and Narmada river basins, stage or discharge records span roughly the last 1 to 2 centuries.

Data regarding all high-magnitude floods since 1876 and stage data for great floods since 1727 are available for the Surat gauging site (Figure 1 *b*), located close to the mouth of the Tapi River[5]. The data indicate that since 1727 at least 33 large floods have occurred on the Tapi River and the largest on the river occurred in 1837. The 1968 flood was the largest in the twentieth century with a maximum peak discharge of 42,450 $m^3 s^{-1}$. In comparison, annual peak stage data at Baroch (Figure 1 *a*), situated close to the mouth of Narmada River, indicate that since 1887 (beginning of record) the highest flood level was recorded in 1970 (69,400 $m^3 s^{-1}$), followed by 1968, 1973 and 1944 floods[1].

Time series analysis of the gauge records by Kale[6] indicates that the flood levels/magnitudes were lower during the early part of the twentieth century (between 1900 and 1940) and that the frequency of great floods has increased substantially during the post-1950 period.

To establish whether the biggest flood in 1970 on the Narmada River and in 1968 on the Tapi River had precedence in the geological records, palaeoflood studies were carried out in the two basins. Another objective of the study was to reconstruct the chronology and magnitude of extreme floods in the two basins.

Sedimentary records of palaeofloods

The Tapi and Narmada rivers flow through bedrock gorges in some stretches. Stable bedrock channels offer a unique environment where flood deposits may be preserved for several centuries to millennia at sites not subjected to scouring by floodwaters[7]. The bedrock gorges of the two rivers have preserved evidence of palaeofloods in the form of flood-transported coarse deposits and fine-grained slackwater flood deposits[1,8]. The use of slackwater deposits for palaeoflood reconstruction is now well established in stable-boundary fluvial reaches[7]. Slackwater deposits consist of fine sand and coarse silt that are deposited in areas of backwaters or diminished flows by sediment-laden floodwaters[7]. The sediment size of slackwater deposits is determined by the lithology of the upstream area, and by the competence of the flow[1,7]. Large floods in the gorges of the Narmada and Tapi rivers generate high values of bed stress and are very erosive. As a result, the flood records are preserved only within sheltered tributary mouths and channel margins[1,8,9]. Small tributary mouths are the most common sites if the tributaries have small catchment areas and the tributary water-mass during large floods on the main river is relatively low.

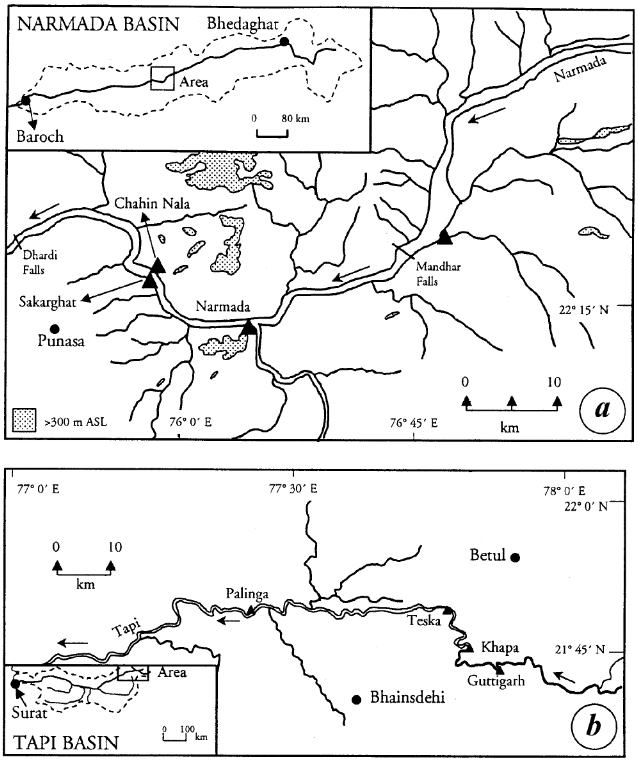

Figure 1. Location of the study areas. ***a***, The central Narmada Basin; ***b***, Upper Tapi Basin. Triangles represent the palaeoflood sites.

Late Pleistocene and early Holocene floods

Quaternary alluvium is widespread within the wide valley sections of the Narmada and Tapi rivers. These deposits represent more or less continuous accumulation in response to late Quaternary palaeoclimatic changes, but are not stacked successions of sedimentary units related to single or multiple flood events. Two sites located within the bedrock gorges, namely, Bhedaghat on Narmada River and Guttigarh on Tapi River have provided evidence of such pre-historic flood events. The well-established evidence of large floods during late Pleistocene is found at Bhedaghat, near Jabalpur (Figure 1 *a*). Here, late Pleistocene deposits are exposed on the right bank of a 130 m wide, palaeochannel of the Narmada River[10,11]. The modern channel flows through the famous Marble Gorge. A 60 cm-thick layer of imbricated boulders (average 35 cm) occurs more than seven meters above the bed of the palaeochannel. Similar imbricated gravelly layers occur in the overlying units also. Whilst to move such coarse gravel along the bed, at least 60 Nm^{-2} of boundary shear stress is required[12], flows with very large bed shear stress (> 10^3 Nm^{-2}) alone can lift such large bedload across flood plains that are usually characterized by low-energy flows[10]. This implies that single or multiple catastrophic floods emplaced the boulders[10]. A ^{14}C date of shells occurring in the overlying unit is about 25,160 ± 550 years BP (AN6619)[11] indicating that an extraordinary flood or a series of great floods occurred several millennia before the Last Glacial Maximum (LGM) on the Narmada River.

In the upper Tapi Basin, the river has developed incised meanders in Deccan Trap basalts. Older flood deposits were located at Guttigarh (Figure 1 *b*) along the margin of the incised channel of the Tapi River. The light-coloured sedimentary sequence is about 4 m thick (Figure 2 *a*). About 5–6 stratigraphical units could be identified (Figure 3 *b*). Particle-size analysis of samples suggests that the upper 2 m sequence dominantly consists of silty-clayey sediments and the underlying units are characterized by well-sorted medium to fine sands. Well-rounded pebbles occur intermittently in the lower units. By and large, all the units are structureless, suggesting rapid deposition of the sediments from suspension. A large number of fossilized freshwater shells and a few mesolithic artifacts occur within the sediments. The deposits are weakly to strongly lithified by calcium carbonate, indicating the antiquity of the deposits. A radiocarbon date of the shells occurring about 2 m below the surface is about 8510 ± 100 years BP (A8468) in age, implying that the deposits were laid down during the early Holocene period. Mesolithic artifacts were also discovered in this unit.

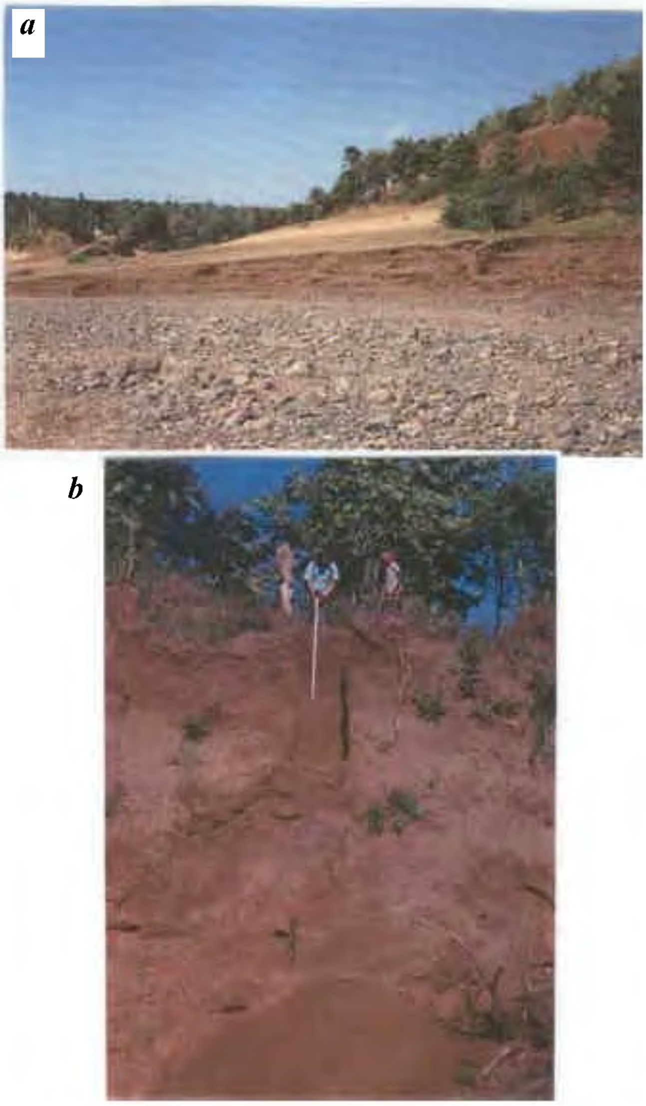

Figure 2. ***a***, Photograph of the early Holocene flood deposits (light coloured) and late historical slackwater deposits (dark coloured) on the left bank of the Tapi river at Guttigarh. ***b***, Narmada slackwater flood deposits at Sakarghat.

Determination of the actual number and magnitude of floods that may have occurred and left these deposits is difficult. Lithification and absence of noteworthy variation in the textural characteristics has made the identification of individual stratigraphic units difficult. Nevertheless, considering the stratigraphical and sedimentological characteristics of the late Holocene slackwater deposits and the thickness of these early Holocene palaeoflood deposits (ca. 4.0 m) it is most likely that the deposits were emplaced by multiple floods during early Holocene. That the deposits were not emplaced by one flood event is also suggested by the occurrence of hillslope wash material at roughly 40 cm and 180 cm below the surface (Figure 3 *b*). Similarity in the distribution of particle size of flood sediments implies that the hydraulic energy available for transport was consistently uniform. Further, since the top of the early Holocene deposits is higher than the late Holocene slackwater deposits, it is reasonable to infer that the flood stage during early Holocene was higher than the late Holocene flood levels. Such an inference can be arrived at because the channel boundaries are resistant and significant changes in the channel geometry are unlikely. Thus, it appears that multiple episodes of high floods may have occurred during the early Holocene in the Tapi River and the flood sediments could have been deposited over a period of time ranging from several decades to a few hundred years.

Late Holocene floods

The only evidence of mid Holocene palaeofloods in the form of slackwater deposits has been found at Barjar (22°21′49″N and 76°2′44″E) on the Choral River. This northern tributary of the Narmada River has developed a small canyon in Vindhyan quartzites. Sequences of sandy flood deposits, about 1 to 2 m thick, are present on the channel margins at a few places. Stratigraphical studies indicate the presence of about seven flood units separated by charcoal and hillslope wash material[13]. A ^{14}C date on charcoal, collected from the lowest unit is 5170 ± 135 years BP (A6859), indicating that about half-a-dozen large floods have occurred on the Choral River during the last 5 ka[13]. The occurrence of hillslope wash and archaeological material suggests long breaks between successive floods. Flood sediments and debris occur in crevices in the canyon walls, up to 6 m above the top of slackwater deposits[13].

Continuous sequences of late Holocene palaeofloods spanning several centuries to a few millennia are preserved also at several locations along the main river. Two such well-studied sequences are described below.

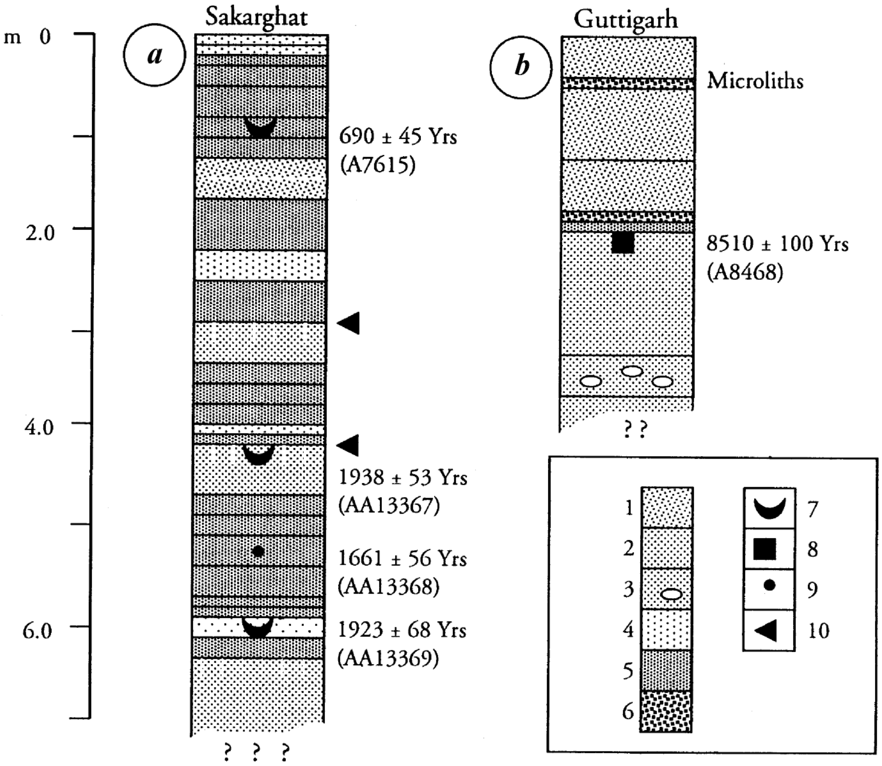

Figure 3. Stratigraphy of the palaeoflood deposits (***a***) at Sakarghat on Narmada River and (***b***) at Guttigarh on the Tapi River. 1, silty clay/clayey silt; 2, fine to medium sand; 3, intermittent pebbles; 4, coarse sand; 5, sandy silt/silty sand; 6, hillslope wash; 7, cultural hearths; 8, shell date; 9, floating charcoal; 10, major breaks. Numbers in brackets represent radiocarbon date lab. numbers.

The Narmada River between Handia and Omkareshwar is incised into resistant Proterozoic rocks of the Vindhyan Supergroup. Several sequences of slackwater deposits were identified in Chahin Nala tributary close to Punasa (Figure 1 *a*)[1,8]. One of the most complete sequences is located about 1.5 km up the tributary and about 16 m above the Narmada low flow level. The sequence is dominated by multiple flood units of sandy silts, silty sands and clays, and preserves evidence of at least 14 floods that have occurred during the last 1700 years. Incipient soil development is observed at the top of several units. This, along with cultural hearths, suggests long breaks between two successive flood events. Radiocarbon dates obtained on organic material in buried soils and a few samples of charcoal suggest that about 1–4 floods prior to 1720 ± 185 years BP, about 5 floods between 1720 ± 185 yrs BP and 650 ± 170 years BP, and about 4–5 large floods after 1950 AD (perhaps 1961, 1968, 1970 and 1973 floods) can be identified[8]. It is interesting to note that there is no record of large floods between 650 ± 170 years BP and 1950 AD in this sequence. Sedimentary records of floods of this period are preserved at lower level as inset deposits, close to the confluence of Chahin Nala and the Narmada River. Radiocarbon ages from this sequence range between 445 ± 60 years BP and 315 ± 65 years BP[1].

The longest continuous sequence of floods spanning at least the last 2000 years is located at the confluence of an unnamed tributary and the Narmada River, at Sakarghat (Figure 1 *a*; Figure 2 *b*)[9]. The flood deposits form a large bench and the top of the deposits is 21 m above low water level[9]. The units are dominated by sand (40–90%). The top 3–4 flood units perhaps represent 1961, 1968, 1970 and 1973 floods, and are coarsest indicating higher flood velocities. Evidence of human activity (hearths, iron slag, etc.) is present in the lower nine and upper six flood units. The individual flood units typically fine upward from sandy-silt to silty-clay. Many flood units are structureless and suggest rapid deposition of suspended material. Two major breaks are indicated by the occurrence of incipient soil, characterized by calcrete filament impregnation (Figure 3 *a*). Considering the changes in the sedimentological and stratigraphical characteristics, the sequence at Sakarghat was found to consist of about twenty-six flood units, which are grouped into four distinct series. The flood chronology of the largest floods on Narmada at this section contains evidence of about 3 large floods after 1950 AD, about 8–9 floods between 1000 and 1400 AD, about 6–7 floods between 400 and 1000 AD and at least 9–10 floods between the beginning of the Christian era and 400 AD[9]. On the basis of texture, elevation, and thickness of the flood units, the periods

400–1000 AD and post-1950 AD represent periods of extreme floods. The former was also the time of reduced human activity in this area[9]. Hydraulic modelling of the reach by Kale *et al.*[1] indicates that the highest slackwater deposits were emplaced by flood discharges close to 55,000 $m^3 s^{-1}$. The modelling further indicates that the discharges of the post-1950 floods were greater than the palaeofloods[1]. Interestingly, in this sequence also there is no evidence of large-magnitude floods between 690 ± 45 yrs BP and 1950 AD.

Evidence of frequent extraordinary large floods during early historical period has also been indicated by archaeological studies at Navadatoli and Khaparkhera, about 100 km downstream of Sakarghat[14]. Most of the early historical settlements are located some distance away from the river channel, suggesting that the settlements were established to avoid effects of unusually large floods[14].

Slackwater deposits in the upper Tapi Basin occur in two major geomorphic situations – as benches parallel to the channel and at the mouth of tributaries. Some of the best sequences were located at Guttigarh, Teska and Khapa (Figure 4) in the Bhainsdehi Gorge along the margins of the Tapi River (Figure 1 *b*). The Guttigarh palaeoflood site is at the inner bend of the Tapi River[1]. Two distinct generations of flood deposits were apparent in the field: Early Holocene slackwater deposits, presently exposed at a higher level and draping the lower slopes of the gorge wall (described earlier); and a younger sequence of slackwater deposits occurring close to the channel bed and inset in the older deposits (Figure 2 *a*). Within the younger sequence, the upper 4–5 units yielded post-1950 AD ^{14}C dates (perhaps representing 1959, 1968 and 1970 floods, as per gauge records) and cover an underlying sequence of sandy or silty-sandy units with a minimum age of 156 ± 52 years BP (perhaps representing 1727 or 1776 historical flood) and a maximum age of 240 ± 50 years BP (calibrated age 1660 AD). Hydraulic modelling[1] suggests that the highest flood deposits at this site were associated with floods close to 4000 $m^3 s^{-1}$. At Teska the slackwater deposits occur on the right bank of the Tapi River. The sequence is about 2 m thick and contains evidence of 6–9 floods (Figure 4). Radiocarbon ages range from post-1950 to 225 ± 40 yrs BP. The upper units perhaps represent the recent floods of 1959, 1968 and 1970. The third flood sequence is exposed on the right bank of the Tapi River at Khapa (Figure 4). The section at this site is about 2.5 m thick and reveals the presence of at least 13 flood units. Radiocarbon dates of three charcoal samples suggest that the deposits were emplaced by floods later than 380 ± 45 years BP On the whole, in the Bhainsdehi Gorge the sedimentary sequences have recorded only the late historical flood history. These sequences are comparable to the younger flood sequences preserved at lower level as inset deposits, close to the confluence of Chahin Nala and the Narmada River. One of the main reasons for such shorter records is that, unlike the gorges

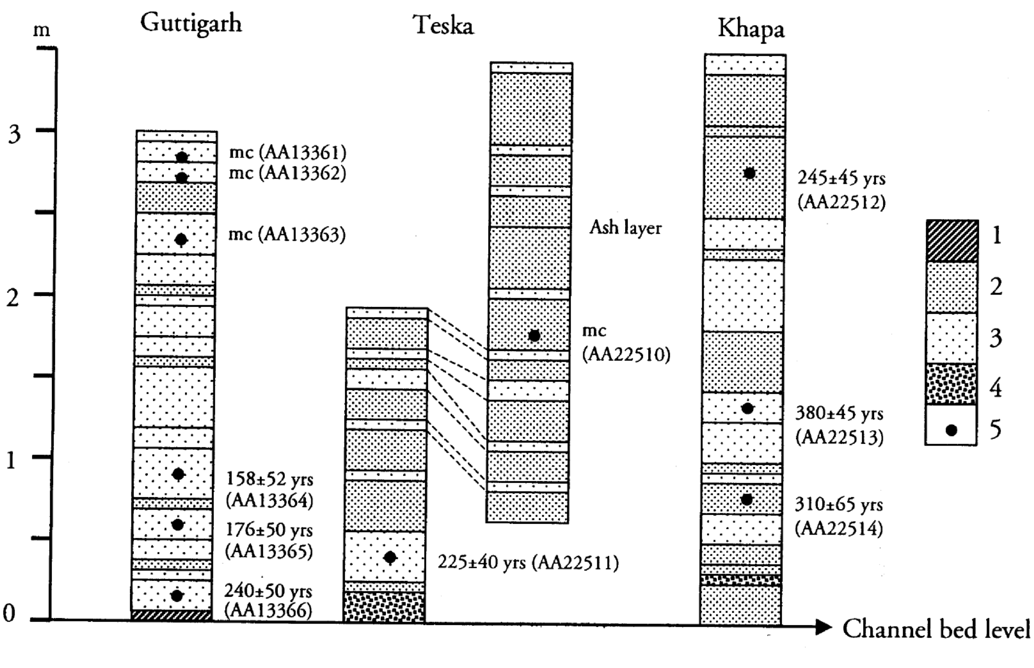

Figure 4. Tapi slackwater deposits at Guttigarh, Teska and Khapa sites. 1, silty clay; 2, sandy silt/silty sand; 3, medium to fine sand; 4, pebbly gravel; 5, charcoal; mc, modern carbon. Numbers in brackets represent radiocarbon date lab. numbers.

of the Narmada River, the Tapi gorge is very narrow and there are not many sheltered geomorphic sites that are protected from scouring by floodwaters. The second reason has to do with the residence time of the fluvial archives, in high-energy environments.

In general, the preservation potential of flood deposits within bedrock gorges of flood-dominated rivers is low because of high-energy conditions and frequent erosion. It is evident from the discussion in preceding paragraphs that palaeoflood records older than ca 2 ka in the Narmada Basin and earlier than 0.4 ka in the upper Tapi Basin have not been found. In view of the flood-prone nature of these two rivers, it is unlikely that major floods have not occurred during the pre-historical period in the Narmada Basin and early-mid historical period in the Tapi Basin. It is most likely that the pre-existing slack-water deposits were eroded and removed by a powerful flood. This inference is supported by erosion of a 300-year record of floods on the Tapi River at Guttigarh during a major flood in 1994. Further, archaeological studies in the central Tapi basin suggest that many of the early historic and proto-historic sites may have been abandoned due to recurring large floods on the Tapi River[15]. In other words, this implies that large floods have repeatedly occurred throughout the historical period and even earlier on the Tapi River. This therefore, indirectly provides evidence of a highly erosive catastrophic flood on the Tapi River approximately at the beginning of Little Ice Age (ca. 300–400 yrs BP) and a severe flood or series of large floods on the Narmada River at the commencement of the Christian era.

In summary, the flood records of the Narmada indicate that extraordinary floods have been the norm rather than an exception during 400–1000 AD and post-1950 AD. Floods of lower magnitude and frequency generally characterized the period 1400 to 1950 AD. Although comparable early historical records from the Tapi River are missing, in view of the coincidence of the modern great flood events (1944, 1959, 1968 and 1970) in the two basins, it is reasonable to infer that the Tapi Basin has also undergone similar changes in the flood frequency and magnitude during the last 2 ka.

Monsoon rainfall and palaeofloods

Any inference regarding palaeomonsoon conditions based upon fluvial or flood records requires a clear relationship between the rainfall conditions and flood magnitude-frequency. Comparison of modern flood records and monsoon rainfall indicates that the monsoon conditions play an important role in changing flood magnitudes. Analysis of about 100 year flood records of five large Indian Peninsular rivers, including Tapi and Narmada, has revealed that there is a strong tendency for periods of high and low floods to coincide with periods of high and low monsoon rainfall respectively[6]. The analysis indicates that below-average (low) rainfall conditions prevailed between 1900s and 1930s, which was a period of stable zonal monsoon conditions over India[16] and above-average (high) rainfall conditions existed from 1870s to 1900s and 1940s to 1960s, when less stable meridional monsoon conditions prevailed[16]. Both Tapi and Narmada flood records show that the frequency and magnitude of floods was significantly lower between 1900s and 1930s and some of the largest floods recorded on the two rivers occurred in the 1940s–1960s (ref. 6). This relationship suggests that the response of the two large rivers of the Deccan Peninsula is clearly linked to long-term variability in the monsoon conditions.

The late Holocene palaeoflood sequences from central Narmada basin indicate marked absence of large-magnitude floods during the last 700 radiocarbon years in general and last 400 radiocarbon years in particular[8,17]. This period of low floods broadly corresponds with the widespread Little Ice Age (LIA)[17], which was dominated by cooler temperatures, reduced monsoon rainfall and increased frequency of droughts[17–19]. Identical pattern of flood changes has also been indicated by investigations of the palaeoflood records in the Godavari, Krishna and Luni rivers[8,17,18], suggesting that this was a regional phenomenon. The highest flood of 1837 on the Tapi River appears to be associated with transition towards warmer conditions at the end of LIA.

The sedimentary records from upper Tapi Basin have provided evidence of series of large floods during early Holocene. These can be linked to well-established evidence of significant warming and strengthening of the southwest monsoon over the Indian subcontinent during the post-glacial period[20–24]. The intensification of southwest monsoon not only increased monsoon rainfall dramatically over much of the Indian region but also increased the frequency of flood-generating cyclones[25]. The multi-proxy palaeoclimatic records also show that the monsoon weakened after about 5 ka[26]. This may account for the general lack of evidence of palaeofloods of this period from any of the river basins studied so far.

The Bhedaghat flood-transported boulders were deposited by rare, extraordinary floods sometimes during isotope stage 3, which was characterized by weaker summer monsoon conditions over India[25] and widespread aggradation in western and central India[11,14]. Thus, the Bhedaghat flood event seems to be associated with the late Pleistocene aggradational phase.

These relationships suggest that the long-term fluctuations in the frequency and magnitude of floods are not independent of long-term variations in monsoon precipitation, and are linked to fluctuations in the monsoon circulation patterns and associated changes in the frequency of tropical storms.

Conclusion

The west-flowing Tapi and Narmada basins lie in a southwest monsoon-dominated, and geomorphologically and tectonically active region, with frequent heavy flood-producing storms. Although the modern flood records are unusually comprehensive, the flood history of the earlier period is not well documented. Geomorphic investigations of sedimentary records of past floods in bedrock gorges of the two rivers reveal evidence of series of major floods during the early Holocene humid phase in the upper Tapi Basin, and an extraordinary flood or floods during glacial period in the upper Narmada Basin. Relatively, the late Holocene palaeoflood records are better preserved. Stratigraphical studies and dating of such deposits at several sites indicate century-scale variations in the flood frequency during the historical period. The palaeoflood records have also provided evidence of temporal clustering of large floods. A diagrammatic summary of flood history of the two basins is given in Figure 5. In general, the records reveal absence of large-magnitude floods during the late Middle Age and Little Ice Age (ca. 700–400 years BP). There is also evidence of clustering of low-frequency, extreme floods between 400 and 1000 AD, and into the most recent period (post-1950). In addition, a catastrophic flood on the Tapi River at the beginning of LIA (ca. 300–400 years BP) and a highly erosive flood on the Narmada River at the commencement of the Christian era, have also been inferred from the palaeoflood records. Studies further show that while the post-1950 floods were the largest during historical period, the early Holocene floods were largest at least in the Holocene. On the basis of modern analogues, it appears that the century-scale variations in

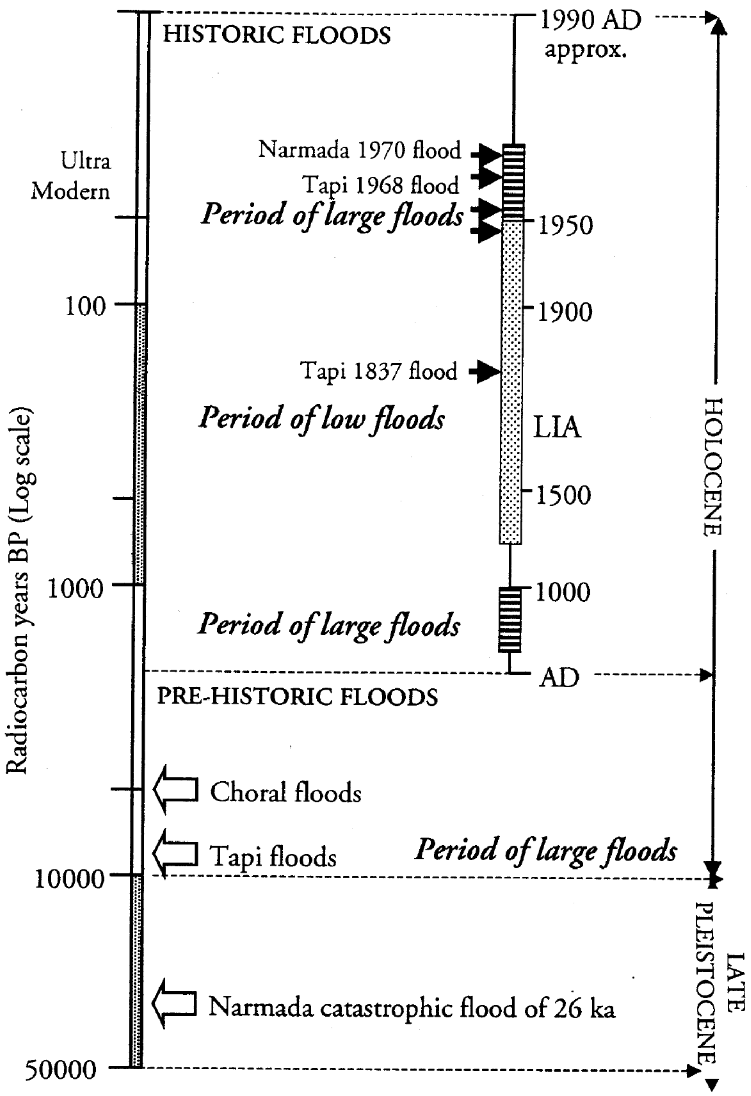

Figure 5. Tentative chronology of floods on the Narmada and Tapi rivers based on modern, historical and palaeoflood records. LIA, Little Ice Age.

the flood magnitude and frequency in the two basins are intimately linked to long-term fluctuations in the monsoon rainfall.

Recent studies, based on modern gauge records and modelling, have provided indications of increasing numbers of great floods in the largest river basins over the past 100 years, globally in general, and in South Asia in particular[27,28]. It has been suggested that floods are likely to continue to become more frequent in the near future[27,28]. The only way of enhancing credibility of such estimates is to generate real data regarding past occurrences of extreme floods. It is therefore, necessary to develop long-term palaeoflood data sets at multiple localities in all the major river basins of the monsoon-dominated regions.

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ACKNOWLEDGEMENTS. This research was supported by DST. Radiocarbon dates were provided by University of Arizona-NSF-AMS Facility. We thank S. N. Rajaguru, Y. Enzel and Lisa Ely for helpful discussions. Review by Avijit Gupta was very helpful in preparing the final version of this paper.