

Palaeoflood hydrology of the fluvial continental records of western India: A synthesis

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ABSTRACT

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Palaeoflood hydrology has emerged as an important tool to infer quantitative and qualitative aspects of ungauged floods based on their physical evidence. Palaeoflood studies in India have largely been undertaken in the rivers of Peninsular India, western India, Ganga plains and the Himalayas to determine the magnitude and age of extreme floods and their connection to variations in the monsoon intensity. Usually, the alluvial domains are unfavourable for the occurrence and preservation of flood deposits and related discharge estimation. However, the alluvial rivers of western India owing to their semi-confined banks comprising late Pleistocene sediments provide an opportunity for investigating both, the high magnitude flood events as well as average flow conditions. In this synthesis we concisely review the recent palaeohydrological studies in western India in terms of flood magnitude, occurrence of extreme events and its relation to the southwest monsoon variability over various time scales. Based on palaeo-fluvial reconstructions, the sedimentation pattern during late Pleistocene appears to be related to changes in channel gradient and the water surface width rather than to discharge variability. On the other hand, the aggradation in channels during early Holocene was largely controlled by the huge sediment influx and the incision that followed was in response to the increase in the discharge and competence of the river flow. The slackwater records from the bedrock channels have revealed that the large magnitude flood events occurred during wet climate phases during the last two millennia. A clustering of high magnitude events at climatic transitions and arid periods during mid-late Holocene has been surmised. Further the flood associated deposits delimited within Quaternary fluvial landforms and channel morphology are vital as these allow quantification of past flood discharges, velocities and stage levels and thus improve the future flood predictions.

Key-words—Palaeoflood hydrology, Fluvial continental records, Regime-based estimation, Palaeodischarge, Western India.

INTRODUCTION

THE continental records are direct proxies of rainfall variability in the Indian sub-continent where Indian Summer Monsoon (ISM) is a major climatic entity (Chamyal & Juyal, 2008). The climatic changes in river basins are therefore largely associated with high-magnitude flood events and the fluvial deposits carry a subtle impression of the hydrological regime (Sridhar & Chamyal, 2010). The changes in the flood regime conditions over the Indian region are linked to fluctuations in the monsoon intensity and associated phenomenon on different timescales (Kale, 2008). The palaeoflood records are hence significant for understanding the magnitude and frequency of large floods and related monsoon conditions and also for a dependable prediction in the future (Baker, 1987). Alluvial sedimentary records are the archives of river response to periods of higher and lower discharge allowing reconstruction of past river flows;

average flows of low to moderate magnitude and frequency, or infrequent high magnitude events (Wohl & Enzel, 1995). However, the sediment records of large-magnitude floods are selectively preserved, whereas deposits from smaller floods are more likely to be removed by subsequent erosion due to their proximity to the active channel (Ely & Baker, 1985). The high magnitude flood events 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 Quaternary palaeohydrology of floods also involves regime-based studies of alluvial rivers and sediment transport studies for competence and capacity of the flow (Costa, 1983). For alluvial rivers a large number of empirical relationships are available for calculating the flow characteristics of ancient rivers from the preserved

morphology and sediments (Schumm, 1968). The accelerated erosion and sediment deposition on floodplains also serve as proxy for multiple phases of higher flood frequency in many river basins (Macklin *et al.*, 2006). According to Baker (2008) studies on identification and analyses of palaeoflood deposits are finding increasing applications in archaeological, palaeoclimatological, palaeoecological and planning contexts.

In India, the large spatial and temporal variations in the monsoon and flood dominated rivers, palaeoflood hydrological approach finds good scope for predicting rare, large floods as well as for hazard management (Kale, 2008). Palaeoflood sites have been investigated on the rivers of Peninsular India, western India, Ganga plains and the Himalayas to determine the magnitude and age of extreme floods, understand their temporal distribution and linkage with climate variability based on field evidence, geochronology and hydraulic modelling (Baker *et al.*, 1995; Kale, 2008; Sridhar & Chamyal, 2018; Srivastava *et al.*, 2017; Sharma *et al.*, 2021).

Here we briefly summarize the recent palaeohydrological studies in India and synthesize the data on palaeoflood hydrology on the fluvial continental records of western India in terms of flood magnitude, occurrence of extreme events and its relation to the monsoon variability and climatic conditions over various time scales.

PALAEOFLOOD STUDIES IN INDIA

Palaeoflood studies in India (Fig. 1a) were initiated in the dynamic and monsoon dominated Narmada River by Baker *et*

al. (1995) and Ely *et al.* (1996) and subsequently in the Tapi River by Kale *et al.* (2003) (Fig. 1b). Slackwater deposits have been reported from the alluvial reaches of the mainland Gujarat rivers (Fig. 1b) (Sridhar, 2007a, 2009; Sridhar *et al.*, 2014, 2016) where large magnitude flood events were observed to cluster at climatic transitions or periods of aridity during the mid-late Holocene Period (Sridhar & Chamyal, 2018). The palaeoflood records from the Himalayan rivers have suggested that changes of flood frequency were caused by variations of monsoon rainfall and large floods occurred during warm and wet climatic phases which may or may not be related to the glacial lake outbursts/ landslide lake outbursts (Wasson *et al.*, 2013; Srivastava *et al.*, 2017; Sharma *et al.*, 2017, 2021). In the Ganga plain, the conditions are not suitable for slackwater deposition however, some regime-based estimates have been attempted (Jain & Sinha, 2003; Shukla & Singh, 2004; Singh *et al.*, 2021). The peninsular rivers have also preserved flood records spanning 1 to 2 ka largely related to wet climate (Thomas *et al.*, 2007; Kale *et al.*, 2010) with the exception of the Kaveri River records where distinct flood clusters have been observed during the times of major shifts in the monsoon climate (Goswami *et al.*, 2019).

The fluvial continental records in the Indo-Gangetic plain, central and western India and some eastern and southern Indian River basins are extensively studied for Quaternary climatic reconstruction and suggest that the nature of geomorphic and stratigraphic response of a fluvial system depends upon its environmental setting and the magnitude and duration of a climatic perturbation (Chamyal & Juyal,

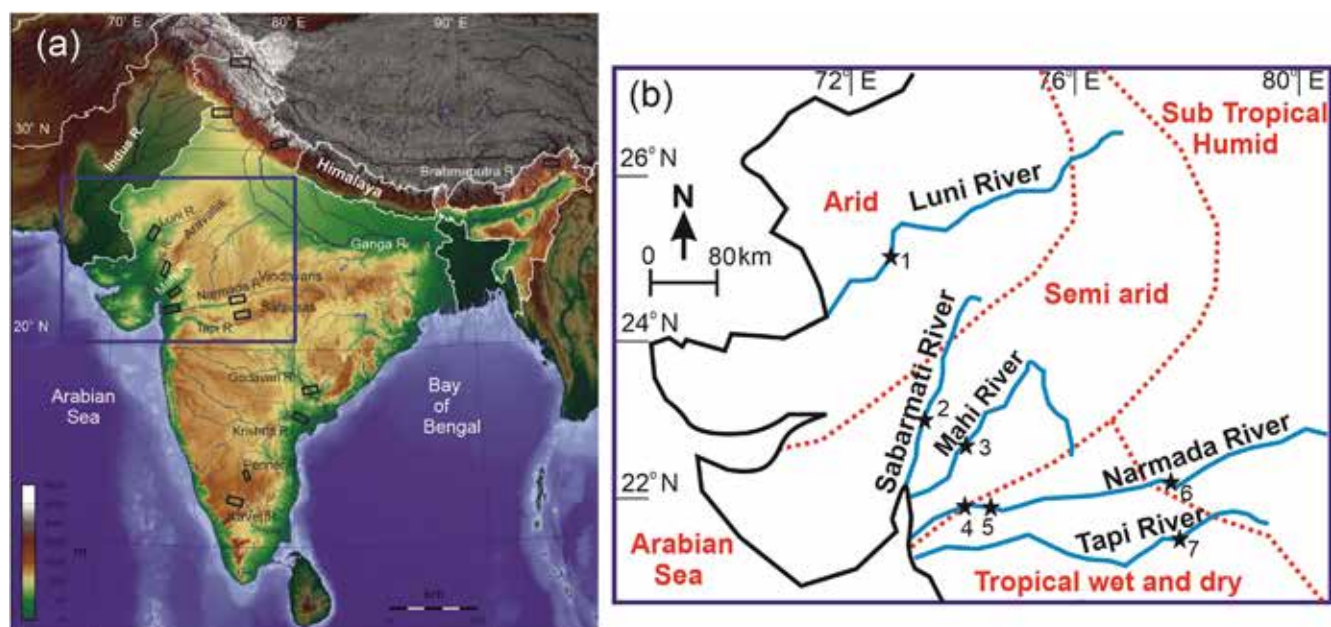


Fig. 1—(a). Relief map of India (based on DEM from Maps of India) showing the palaeoflood study areas on various rivers. The rectangle marked in blue represents the area of Figure 1(b). (b) Climatic zones, the major west flowing rivers and palaeoflood sites in western India. The numbers 1–7 show important palaeoflood sites on Luni River at Bhuka (1), on Sabarmati River at Juna Sangpur (2), on Mahi River at Dodka (3), on Narmada River at Ranipura (4) and Dharnacha (5) in the lower reaches and Sakarghat (6) in the middle reach, on Tapi River at Guttigarh (7).

2008). The sediment records under various physiographic settings provide scope to demarcate palaeoflood markers and related climatic perturbations. The palaeoflood evidence may be in form of the fine-grained sediments transported in suspension and deposited much away from the river channel (slackwater deposits SWD) (Ely & Baker, 1985) as well as coarse-grained bedload pulses or sheets preserved within the sediment sequence (Knox, 1985). Most of the palaeoflood data until recently came from the ideal bedrock gorge settings using slackwater deposits however, recent studies have clearly brought out the scope for generating palaeoflood data outside the traditional physiographical setting of bedrock gorges (Sridhar, 2007a, 2009; Sridhar *et al.*, 2014). The late Pleistocene palaeoflood studies mainly rely on discharge estimates based on clast size and channel morphology (Sridhar & Chamyal, 2010; Sridhar *et al.*, 2013; Singh *et al.*, 2021). Nonetheless, the data on past hydrologic changes drawn from palaeoflood analyses of the rivers of India which have short gauging records, can be highly useful in modelling and predicting the nature of future climate change impacts (Kale, 2008). During the last two decades there has been an increase in the amount of palaeoflood data generated in India however, given the size of the country, the extensive drainage network and the tremendous scope, the available palaeoflood information is very scanty.

FLUVIAL RECORDS OF WESTERN INDIA

The western Indian region forms the southern margin of Thar Desert flanked by the Arabian Sea in the west and the Aravalli and Central Mountains in the east. The lithology of the region comprises the Deccan Trap basalts, the rocks of the Aravalli Super Group, viz. phyllites, schists, quartzites, ultramafics, granites and gneisses and the Quaternary sediments. A large part of western India is occupied by the Alluvial Plains (Merh & Chamyal, 1997). The channels are deeply incised either in bedrock or alluvium, and even high flows are insufficient to fill the whole channel (Gupta, 1993). Majority of the rivers here have their catchments in the Aravalli upland and drain through the vast alluvial plains before debouching into the Rann of Kachchh or Gulf of Cambay. These rivers, from north to south, are the Luni, Banas, Rupen, Sabarmati, Mahi, Orsang and the Narmada. Here we focus on the Sabarmati, the Mahi, the Narmada and the Tapi rivers, all of which originate in the neighbouring highlands and flow from east to the west, debouching into the Arabian Sea. The Sabarmati and the Mahi River basins are situated in the semi-arid climatic zone, whereas the Narmada and Tapi fall in the sub-humid climate zone (Fig. 1b). The discharge in these river basins is related to the SW monsoon and the passage of monsoon depressions and low pressure systems, either from the Bay of Bengal or the Arabian Sea. Large floods have been recorded on the Mahi, Sabarmati and the Narmada rivers (Krishnamurthy *et al.*, 2009) during

the last few centuries. The river channels are bounded by Pleistocene terrace sediments forming 30–40 m high cliffs that provide resistant boundaries and restrict floodplain widths, channel migration and splay formation (Sridhar, 2007a, 2009).

The basic stratigraphic understanding on the fluvial records of western India is provided by Juyal *et al.* (2006). The three major phases of flood plain aggradation corresponding to the enhanced southwest monsoon suggested by them during the late Pleistocene occurred around >100 ka, 98 ka–69 ka and 49 ka–30 ka. After 30 ka there was an overall decrease in monsoon however, the geomorphic response was variable. A phase of incision after the Last Glacial Maximum due to the strengthening of the monsoon in the sub-humid regions (Juyal *et al.*, 2006) and a weak monsoon represented by aeolian sedimentation in the arid–semi arid regions prevailed (Juyal *et al.*, 2003). The early Holocene has been marked as the period of high intensity erosion and incision in these river basins (Gupta *et al.*, 1999; Maurya *et al.*, 2000). The fluvial sediment records that span the mid–late Holocene are preserved as valley–fill terraces along the channels and within the late Pleistocene cliffs (Chamyal *et al.*, 2003).

It is well established that the continental fluvial records of western India signify the role of monsoon variability during the late Pleistocene–Holocene (Juyal *et al.*, 2006). Since alluvial sedimentary records are the archives of river response to periods of higher and lower discharge, palaeohydrological interpretations concerned with the reconstruction of past–river flows, average flows of low to moderate magnitude and frequency, or infrequent high magnitude events have been attempted in past decade or so (Sridhar, 2007a, b; Sridhar & Chamyal, 2010, 2018; Sridhar *et al.*, 2013, 2014, 2015, 2016).

PALAEOFLOOD HYDROLOGY

The flood related deposits contained within Quaternary fluvial landforms and channel morphology are quite significant as these allow quantification of past flood discharges, velocities and stage levels (Wohl and Enzel, 1995). The sediments of river terraces are studied to determine the competence and regime theory, the largest transported grains, thickness of a flood sediment body and the height of the cross beddings and dimensions of palaeochannels are used for understanding the flow conditions and slackwater deposits for the high magnitude flood quantification, its frequency and magnitude (Etheridge & Schumm, 1978; Komar, 1989). The alluvial rivers of western India provide scope for analyzing both, the high magnitude flood events as well as average flow conditions since the late Pleistocene.

Slackwater palaeoflood deposits

The slackwater flood deposits (SWDs) are vertically stacked sequences occurring at peculiar geomorphic sites where flow velocity decreases and form an important natural

Table 1—Summary of palaeoflood deposits in the rivers of western India (modified after Kale, 2008).

River	Channel type	Gorge	Name of site/ tributary	Number of flood events	Length of record in years	Estimated maximum discharge (m^3s^{-1})	Reference
Narmada	Bedrock	Punasa	Chahin Nala	11–15	1700	52,000	Kale <i>et al.</i> , 1994, 1996, 2003 Baker <i>et al.</i> , 1995 Ely <i>et al.</i> , 1996
			Chota tawa	14–15	1400	—	
			Ramghat	18–19	600	—	
			Sakarghat	26	2000	—	
	Alluvial	—	Karjan river	3	300	—	Sridhar <i>et al.</i> , 2016
			Ranipura	6	700	—	Sridhar <i>et al.</i> , 2015
Mahi	Alluvial	—	Dodka	4	1.7 and 4.6ka	55,000	Sridhar, 2007a
			Poicha	4		—	
			Bhadarva	3		—	
			Kherda	6		—	
			Munpur	2	500	—	Sridhar <i>et al.</i> , 2013
Sabarmati	Alluvial	—	Juna Sangpur	4	1200	15,860	Sridhar <i>et al.</i> , 2014
			Derol	3		—	
			Dedhrota	4		—	
Luni	Bedrock	Sindari	Bhuka	17–22	1000	12,000	Kale <i>et al.</i> , 2000
Tapi	Bedrock	Bhainsadehi	Ghuttigarh–Khapa	13–16	400	4,000	Kale <i>et al.</i> , 1994, 2003

Table 2—Palaeoflood characteristics of important sites in the alluvial reach (modified after Sridhar, 2007a; Sridhar *et al.*, 2014, 2016).

River	Site/ tributary	Physio-graphic setting	El-e-vation above river level (m)	Distance from main channel (m)	Total thick-ness (m)	Mean Thick-ness of SWD unit (m)	Differ-entiating unit	SWD characteristics
Narmada	Karjan river confluence	Tributary mouth	10	200	8	0.5	Light coloured coarse sand	Blocky and compacted clayey silt palaeoflood units with dark clayey layers
Mahi	Dodka	Ravine opening	12	200	8.5	1.0	Slope wash with calcrete nodules	Finely laminated pale brown silt with clay cap-ping; blocky structure
Sabar-mati	Juna Sangpur	Ravine opening	12	150	3	0.3	Slope wash with calcrete nodules	Very fine, massive micaceous sand, laminated silt with clay cap; blocky structure

proxy for multiple large floods (Ely & Baker, 1985). These fine-grained (silty and sandy) deposits are considered as a reliable physical record of water surface elevations reached by successive floods (Kale, 2008). The SWDs, a natural archive of long-term flood frequency and magnitude, occur under various physiographic settings, possess unique sedimentological character, provide chronology and palaeoflood estimates.

The SWDs accumulate in marginal valley settings and the depositional environments commonly include (1) areas of channel widening, (2) severe channel bends and valley expansion, (3) obstacle hydraulic shadows where flow separation causes eddies, (4) back-flooded tributary mouths and valleys (Benito *et al.*, 2020). In western India, the SWDs are located at tributary mouth and ponded zone behind the tributary mouth in bedrock reaches (Kale, 2008). Whereas in the alluvial reaches, the deposition of SWD is related to changes in cross-sectional area as water level

risers during the flood. The expansion settings here include the ravines in the quasi-stable riverbanks, tributary mouths and channel widening (Sridhar, 2007a; Sridhar *et al.*, 2015; 2016). Palaeoflood data has been generated from several sites studied in the bedrock reaches of the Narmada, Tapi and Luni rivers (Kale, 2008) and alluvial reaches of the Mahi, Narmada and Sabarmati rivers (Sridhar & Chamyal, 2018) (Table—1). The sedimentological and stratigraphic characteristics of the palaeoflood deposits in the alluvial reach are summarised in Table 2.

The slackwater flood deposits in the Punasa gorge of central Narmada Basin (Fig. 2a) point to the occurrence 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 of which the periods 400–1000 AD and post-1950 AD represent periods of extreme floods (Kale, 2008; Kale *et al.*, 2003). Water surface profiles for a 2.4 km

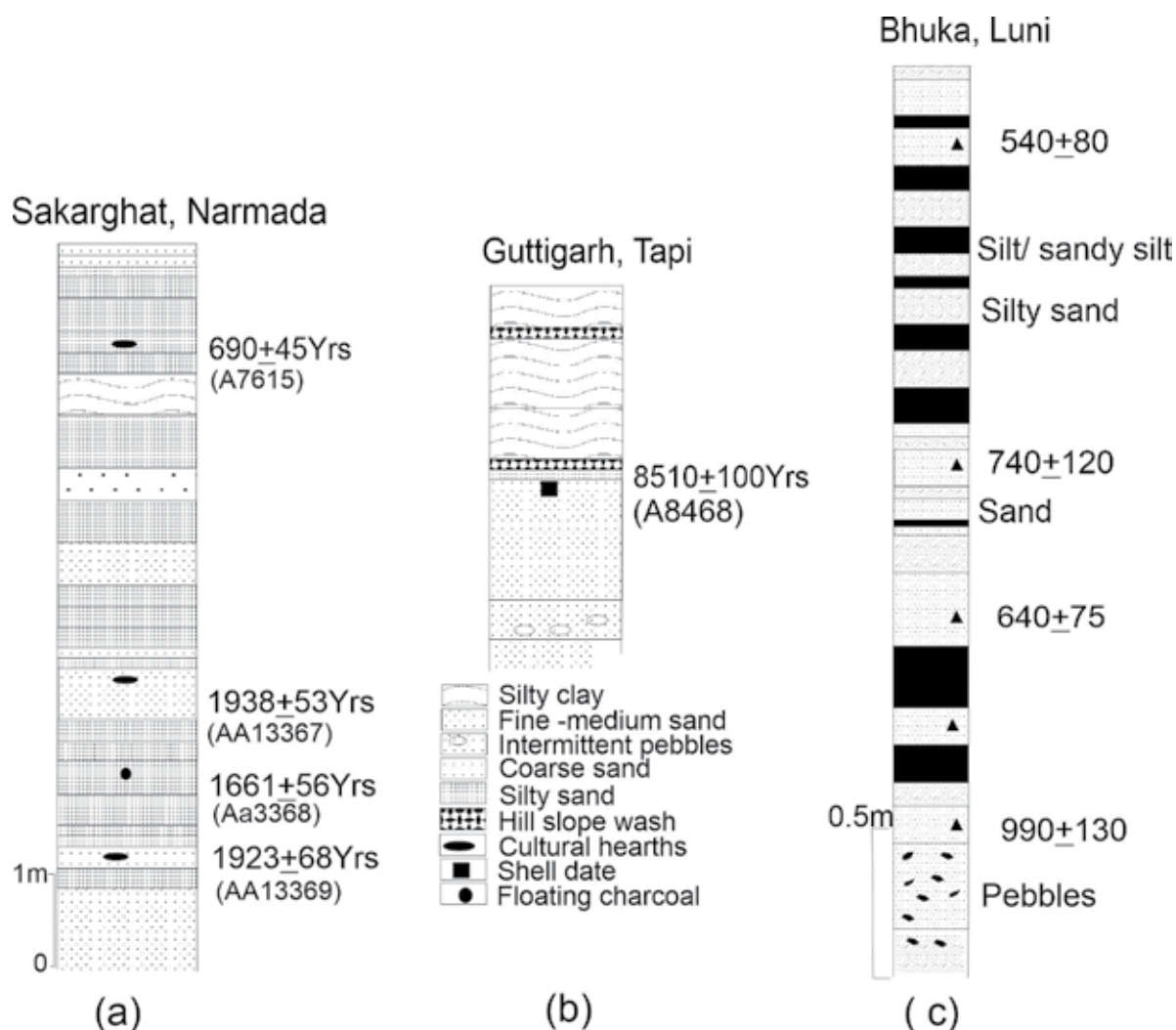


Fig. 2—Stratigraphy of the SWD sequences in bedrock gorges at (a) Sakarghat on the Narmada River and (b) Guttigarh on the Tapi River (redrawn from Kale *et al.* 2003) and (c) Bhuka on the Luni River (redrawn from Kale *et al.* 2000).

reach of the Narmada River at Punasa indicate that the highest slackwater deposits were emplaced by flood discharges close to 55,000 m³/s (Kale *et al.*, 1994). The SWD sequences of the Bhaninsadehi Gorge of upper Tapi River (Fig. 2b) have revealed short term palaeofloods of lower magnitude during the last ca. 400 years (Kale *et al.*, 2003). The palaeoflood deposits in the Sindari Gorge of the lower Luni Basin (Fig. 2c) have revealed at least 17 extreme floods during the past millennium with clustering of floods between 1000 and 500 years (Kale *et al.*, 2000). The palaeoflood records from the bedrock gorges indicate that the preservation potential of flood deposits is low because of high-energy conditions and frequent erosion, suggesting that the long-term flood regime in western India is closely related to monsoonal variability at the regional scale (Kale, 2008).

In the alluvial reaches, most of the SWD sequences have been reported from the ravines that open up almost perpendicular to the main channel (Sridhar, 2007a) with a few sites at tributary junction and tributary backwater (Sridhar *et al.*, 2016). Sizeable sequences of slackwater deposits much away from the channel at elevations of up to 20 m above the river level are preserved in the deeply incised ravines at the meander bends in the alluvial reaches and have been well protected from the annual flooding of the channel as well as any other minor flood events since their deposition. Sridhar (2007a) reported some of the best exposures of slackwater deposits from the Mahi River basin dating back to almost 5 ka. These exhibit a unique blocky character and are separated by the colluvial horizons (Fig. 3a). Four distinct units of slackwater deposition separated by colluvial units have been related to four phases of flood deposition during the mid to late Holocene, two of which correspond to 4.6 ± 1 ka and 1.7 ± 0.5 ka respectively (Sridhar, 2007a). Flood deposits have also been reported from the middle reaches of the Mahi River belonging to late medieval time (Sridhar, 2009) and as recent as 0.46 and 0.28 ka (Sridhar *et al.*, 2013).

In the middle reaches of the Sabarmati River four events of flooding between 1.3 and 0.26 cal ka have been documented (Fig. 3b) and the peak discharge estimations for the SWD using slope-area method suggest a minimum discharge of 15,680 m³s⁻¹ related to the event dated to 0.55 cal ka as compared to the present day peak flood discharge of 7303 m³s⁻¹ (Sridhar *et al.*, 2014). Palaeoflood records observed at the confluence of the Karjan River, a tributary in the lower reach of Narmada (Fig. 3c) indicate occurrence of high magnitude flood events towards the end of the Medieval Warm Period and throughout the Little Ice Age (Sridhar *et al.*, 2016). A pulse of high magnitude flooding events with multiple episodes of rapid erosion and deposition (1.8–1.69 cal ka) has also been observed in the lower reach of Narmada River at Ranipura (Fig. 3d) (Sridhar *et al.*, 2015).

The combination of data presented here indicates that though flooding is broadly synchronous in the river basins of dryland western India, they are at a variance from the

records of the Peninsular rivers and Upper Gangetic catchment (Sridhar & Chamyal, 2018). Based on the flood frequency analysis of the events during late Holocene in the Narmada, Mahi and Sabarmati basins, a maximum frequency of flood events is seen in the Narmada Basin as compared to the Mahi and Sabarmati basins (Sridhar & Chamyal, 2018). The period between 1.2 and 2.1 cal ka witnessed highest frequency of flood events during the last 5 ka (Fig. 4). The high magnitude flood events were coincident in the Mahi and Narmada basins at 1.7 cal ka BP and 0.3 cal ka, in the Mahi and Sabarmati at 0.5 cal ka and in Narmada and Sabarmati at 1.3 cal ka (Sridhar & Chamyal, 2018). Four distinct flood clusters have been identified, the largest cluster being in the time period 0.65–0.2 cal ka with the highest probability at 0.55 cal ka and the other three clusters occurring at 3–2.8, 2.2–1.6, 1.3–1.1 cal ka (Sridhar & Chamyal, 2018). These clusters do not necessarily coincide with the strengthening of the monsoon conditions as the two most widespread clusters at 0.5 and 1.7 ka coincide with the weak monsoon/ climate transition in these river basins of western India (Fig. 4). This further implies that high magnitude flood events cannot be singularly considered as indicators for enhanced monsoon conditions in a region (Sridhar & Chamyal, 2018).

Regime-based palaeoflood estimations

The late Pleistocene records

The exposed late Pleistocene fluvial sediment successions comprise gravel terraces that have been interpreted in terms of the temporal variations in the climate-related palaeofloods that constructed these over longer time-scales (Sridhar & Chamyal, 2010; Sridhar *et al.*, 2013). For instance, the gravel terraces in the lower Narmada Basin are interpreted to have formed by vertically stacked sub rounded gravel to cobble size clasts in an alluvial-fan environment (Chamyal *et al.*, 1997; Sridhar & Chamyal, 2010). The poor to moderate sorting and coarse clast size suggests that flows were sediment laden and related to high magnitude hydrological events that generated high energy floods (Sridhar & Chamyal, 2010; Stokes *et al.*, 2012). Applying the empirical relationship developed by Williams (1984) for coarse sediment, Sridhar and Chamyal (2010) suggested that the unit stream power of the flow depositing the maximum clast size 150 cm, may have been of the order of 853 W m⁻², with bed shear stress of 255 N m⁻² at the fan apex, reducing to 27 W m⁻² and 17 N m⁻², respectively at the distal end. The upland reaches of the Narmada River also indicate similar values for stream power (Kale, 2003), meaning that present-day floods are also capable of transporting similar sediment sizes. The high stream power during the formation of these gravelly terraces ~90 ka (Chamyal *et al.*, 1997) may therefore be related to the high river gradient. The palaeoflood estimates based upon the main competence and regime based methods indicate a discharge of

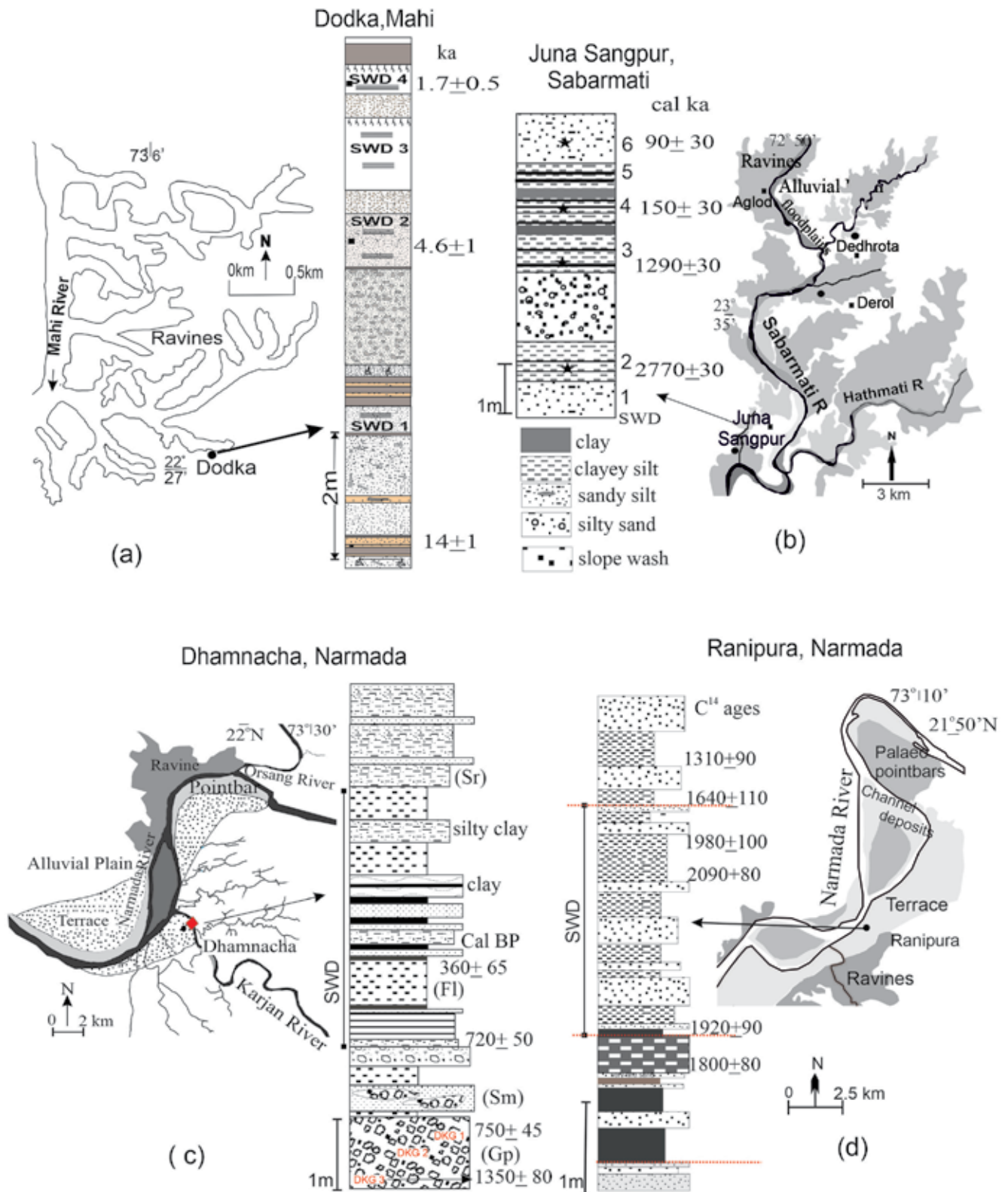


Fig. 3—Geomorphic setting and stratigraphic record of the SWD sequences in alluvial rivers at (a) Dodka on the lower Mahi River (after Sridhar, 2007a), (b) Juna Sangpur in the middle reach of the Sabarmati River (after Sridhar *et al.*, 2014), (c) Dhamnacha at the confluence of Narmada and Karjan rivers (after Sridhar *et al.*, 2016), (d) Ranipura on the lower Narmada River (after Sridhar *et al.*, 2015). For location of the sites also refer Fig. 1b.

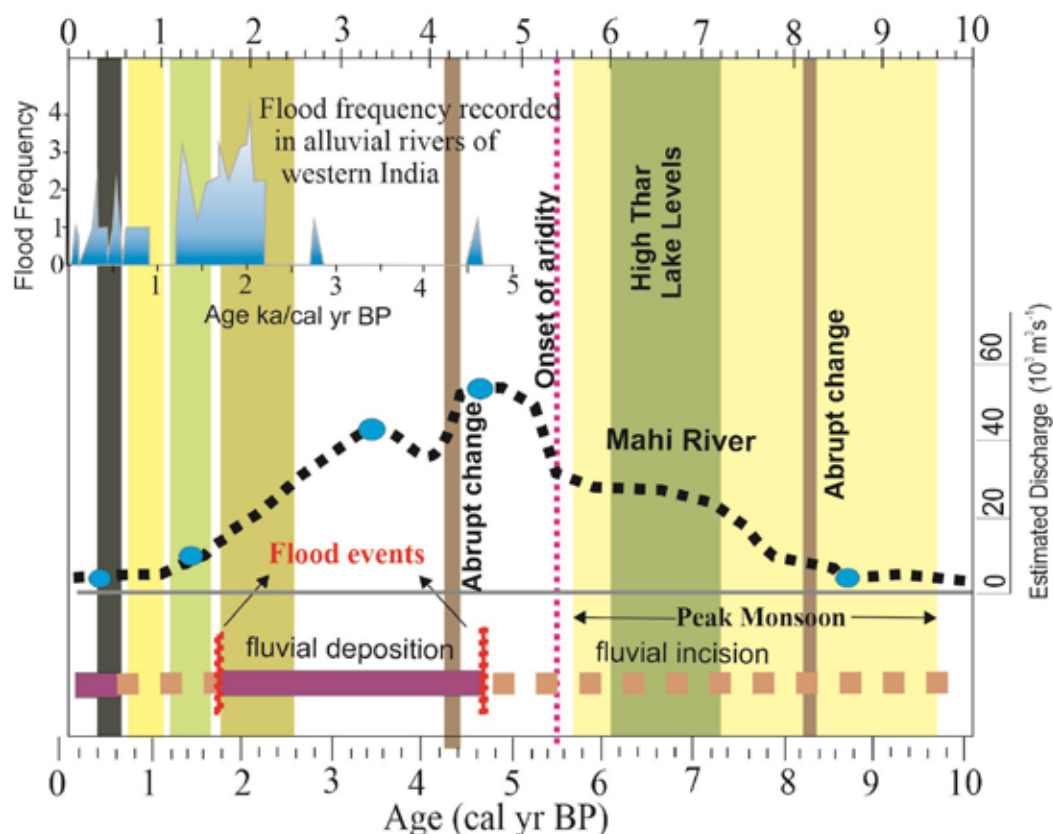


Fig. 4—Summary figure showing the correlation between the flood events in the alluvial rivers of western India and Indian Summer Monsoon activity during the Holocene (modified from Sridhar *et al.*, 2020). The phases of peak monsoon, high Thar lake levels and abrupt climatic changes have been marked from Kale *et al.* (2003). The flooding pattern and discharge of the Mahi River is represented based on Sridhar (2007a, b). The flood frequency recorded from fluvial archives of alluvial plains and fluvial activity are shown from Sridhar & Chamyal (2018).

$\sim 1379 \text{ m}^3\text{s}^{-1}$, a value very close to present day discharge of $1152 \text{ m}^3\text{s}^{-1}$. Based on these palaeo-fluvial reconstructions it appears that the sedimentation pattern of lower Narmada Basin is more related to gradient and the water surface width than to discharge for the high stream power around 90 ka (Sridhar & Chamyal, 2010). The late Pleistocene gravel deposits are also seen in the Mahi, Sabarmati and the Luni rivers however, palaeohydrological estimates are yet to be attempted.

The Holocene records

The Holocene sedimentation record is preserved in the form of terraces and point-bars in the alluvial rivers of western India. The stream competence of the Narmada River depositing sediments in these environments varies between 211 Wm^{-2} and 11 Wm^{-2} and is much lower in comparison with the late Pleistocene deposits (Sridhar & Chamyal, 2010). Discharge during the early Holocene, however, may have been high as is evident from the thickness of the accumulated lithofacies assemblages. The lithofacies association of the terrace sediments varies from gravel at the base, passing upwards into cross stratified sand and capped by finer grained facies,

pointing to a progressively reducing flow regime and lateral accretion related to channel migration (Sridhar & Chamyal, 2010). Estimates from the terrace dimensions suggest that the bankfull discharge was $16,965 \text{ m}^3\text{s}^{-1}$, about 10 times higher than the present-day bankfull discharge (Sridhar & Chamyal, 2010). The palaeocompetence and palaeodischarge analysis of a late Pleistocene–early Holocene gravel terrace in the Mahi River basin showed the unit stream power range between 110 Wm^{-2} and 17 Wm^{-2} indicating high competence flood flows (Sridhar *et al.*, 2013). Based on the equation of Williams (1984), the average discharge estimated was $10\text{--}12 \text{ m}^3\text{s}^{-1}$, whereas the annual peak discharge associated with the maximum cross bed thickness was $\sim 782 \text{ m}^3\text{s}^{-1}$ and based on maximum clast size was $2058 \text{ m}^3\text{s}^{-1}$ much lower (Sridhar *et al.*, 2013) as compared to modern largest flood discharge of $40,663 \text{ m}^3\text{s}^{-1}$ in 1973 (CWC, 2012). These studies on the early Holocene terrace records have suggested that the aggradation in the channels was largely controlled by the huge sediment influx during the early Holocene (Fig. 4) and the incision that followed was in response to the increase in the discharge and competence of the river flow (Sridhar *et al.*, 2013).

Contemporary and palaeo-discharges through the mid-late Holocene in the alluvial reach of the Mahi River basin were also estimated using the terrace and pointbar geometry (Sridhar, 2007b). The estimates indicate that the bankfull discharge of the mid-late Holocene channel was $\sim 55000 \text{ m}^3 \text{ s}^{-1}$ and that of the historic channel was $\sim 9500 \text{ m}^3 \text{ s}^{-1}$, some ~ 25 times and ~ 5 times greater than that of the present ($2000 \text{ m}^3 \text{ s}^{-1}$), respectively. Since the mid-late Holocene, the channel form has changed from wide, large-amplitude meanders to smaller meanders, and decrease in the width/depth ratio, unit stream power and the bed shear stresses have occurred (Sridhar, 2007b). A trend of decreasing precipitation since the mid-late Holocene and channel planform alterations from mid-late Holocene to the present are related to climate-driven hydrological changes rather than to tectonic effects (Sridhar, 2007b).

CONCLUDING REMARKS

The hydrological changes in the monsoon fed and flood prone rivers of western India are directly related to the variations in the monsoon intensity. Therefore, prediction of extreme flood events that are a threat to society becomes important. However, the gauge recorded flood data on major rivers is very short and for smaller tributary rivers, it is not available. Palaeoflood hydrological techniques help in reconstructing the magnitude and frequency of past or ancient floods using geological evidence. The synthesis of data suggests that the application of the palaeohydrological analysis has provided some quantitative constraints on the late Pleistocene and Holocene channel dimensions and patterns, the stream discharge and competence along with inferences on the occurrence of extreme flood events in western India. The inferences on palaeochannel dimensions during late Pleistocene–Holocene based on the fluvial sediment geometry and comparison with the modern channel dimensions has provided a possibility in decoupling the role of climate and tectonics in river aggradation–incision processes.

The palaeoflood hydrological studies on the lower reaches of the rivers of western India have thrown light on the occurrence of extreme events, palaeoflood magnitudes and the monsoon–flood dynamics. The documentation of slackwater deposits in the ravines along the cliffy alluvial banks of these rivers has expanded the scope of palaeoflood hydrology in alluvial rivers. A comparison of the palaeoflood records on extreme events with the palaeoclimate records point towards the occurrence of extreme floods in dry periods or at climatic transitions rather than stable wet periods and may have been caused due to cyclonic storms rising in the Arabian Sea and the Bay of Bengal.

It is beyond doubt that for a large drainage network and fluvial records of western India, the available data are fragmentary and from limited number of palaeoflood sites with small number of geochronological ages being used

for the analyses and inferences. Nonetheless, these studies highlight the significance of palaeoflood hydrology in flood estimation that plays a crucial role in water resources development and planning. There is good scope as well as need to identify and investigate palaeoflood sites on other rivers to generate comprehensive palaeoflood data and further explore the linkage between the extreme flood events and climate variability.

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