Palaeoflood record of high-magnitude events during historical time in the Sabarmati River, Gujarat

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We report the occurrence of large floods in the Sabarmati River Basin during cal AD 1400–1440. Slackwater palaeoflood deposits have been preserved in the highly dissected ravines along the middle reaches of the river, wherein 5–6 discrete flood events have been identified. The minimum discharge that emplaced the highest deposit has been estimated as ~15,680 $m^3 s^{-1}$ and is higher than that recorded (3050 $m^3 s^{-1}$) during the recent 2006 flood. The timing of these high-magnitude flood events in the Sabarmati and adjacent river basins suggests that extreme hydrological events have occurred in response to excess monsoon periods and are largely controlled by the regional climatic conditions. Moreover, these flood events are seen to be broadly synchronous in the alluvial river basins of Gujarat across climatic zones, but are at variance in pattern from the records of the bedrock peninsular rivers.

Keywords: Alluvial plains, flood events, monsoon, palaeofloods, slackwater deposits.

PALAEOFLOOD records are significant for understanding the magnitude and frequency of large floods and related monsoon conditions[1] and also for a dependable prediction in the future. 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[2]. The west-flowing rivers of India are predominantly fed by the southwest monsoon and therefore any available palaeoflood record reveals the past monsoon conditions. The Narmada, Tapi, Mahi and Sabarmati are the four major west-flowing rivers with a long flood history. Whereas the Narmada and Tapi are sub-humid tropical rivers, the Mahi and the Sabarmati flow through semi-arid climatic zone. The flood history of Tapi (sub-humid), Narmada (sub-humid) and Mahi (semi-arid) has been found to be synchronous[3] and peak flood events from early to late Holocene have been recorded[4–6]. However, palaeoflood record from climatically sensitive Sabarmati River (semi-arid) Basin located at the southern margin of the Thar desert has not been investigated so far. The present communication provides fresh records of high-magnitude flood events during the last about 500 years in the alluvial plains of Gujarat from the Sabarmati Basin. An attempt has also been made to explore links between the identified events in the Sabarmati, analogous events from the adjacent river basins across climatic zones and long-term fluctuations in the monsoon rainfall.

The Sabarmati River flowing through the semi-arid western India is a monsoon-dominated seasonal river and remains dry post-monsoon. At times, however, it pushes down very heavy floods that have caused devastation in the city of Ahmedabad, damaged crops in adjacent low-lying areas and filled the gulf with silt[7]. In the last about 100 years, the flood event that occurred in 1973 is considered to be the highest in the basin, but there is no consensus on the actual peak discharge (according to the State Irrigation Department, probable peak discharge was 16,000 $m^3 s^{-1}$). The more recent high-magnitude flood event that occurred in 2006 is better recorded with 8800 $m^3 s^{-1}$ peak discharge[8]. According to the historical records[9,10], high-magnitude floods are also known to have occurred earlier in 1683, 1714, 1739, 1755, 1868, 1927, 1941, 1950 and 1992 suggesting a clustering of flood events. An increase in frequency and magnitude of extreme rain events not only in the Sabarmati, but all over India, has been observed during the latter half of the 20th century[11–13] and this has raised serious questions on the future trends.

The Sabarmati is a seasonal river receiving varied amount of rainfall (450–800 mm) and is located in the semi-arid climate zone. The Basin is bounded by Aravalli hills in the north and northeast; it is 371 km long with 21,674 sq. km drainage area and average discharge of 120 $m^3 s^{-1}$. The Sabarmati River with its origin in Rajasthan flows generally in the SW direction through the Gujarat Alluvial Plains (Figure 1 *a*) and joins the Gulf of Cambay. The Wakal, Sei, Majham, Harnav, Hathmati and Watrak are the main tributaries of the Sabarmati River (Figure 1 *b*).

Palaeoflood slackwater deposit (SWD) is a major evidence used for inference about hydrological parameters of the past flood events[14,15]. 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 SWD[1]. Although the potential for palaeoflood studies in alluvial rivers is generally low[16], the river channels in the Gujarat Alluvial Plains are bounded by indurated late Quaternary sediment cliffs and are highly incised providing scope for accumulation and preservation of SWD[6]. With this understanding, the Sabarmati River Basin was explored for palaeoflood deposits in the alluvial reaches.

During field investigations along the Sabarmati River, profiles with SWD beds were identified at Dedhrota, Derol and Juna Sangpur (Figure 1 *c*), occurring at different levels and with varying thickness. The palaeoflood events have been identified using sedimentological criteria based on abrupt vertical changes in the texture, structure and colour of the sediments, clay capping and depositional discontinuity between two flood events in the form

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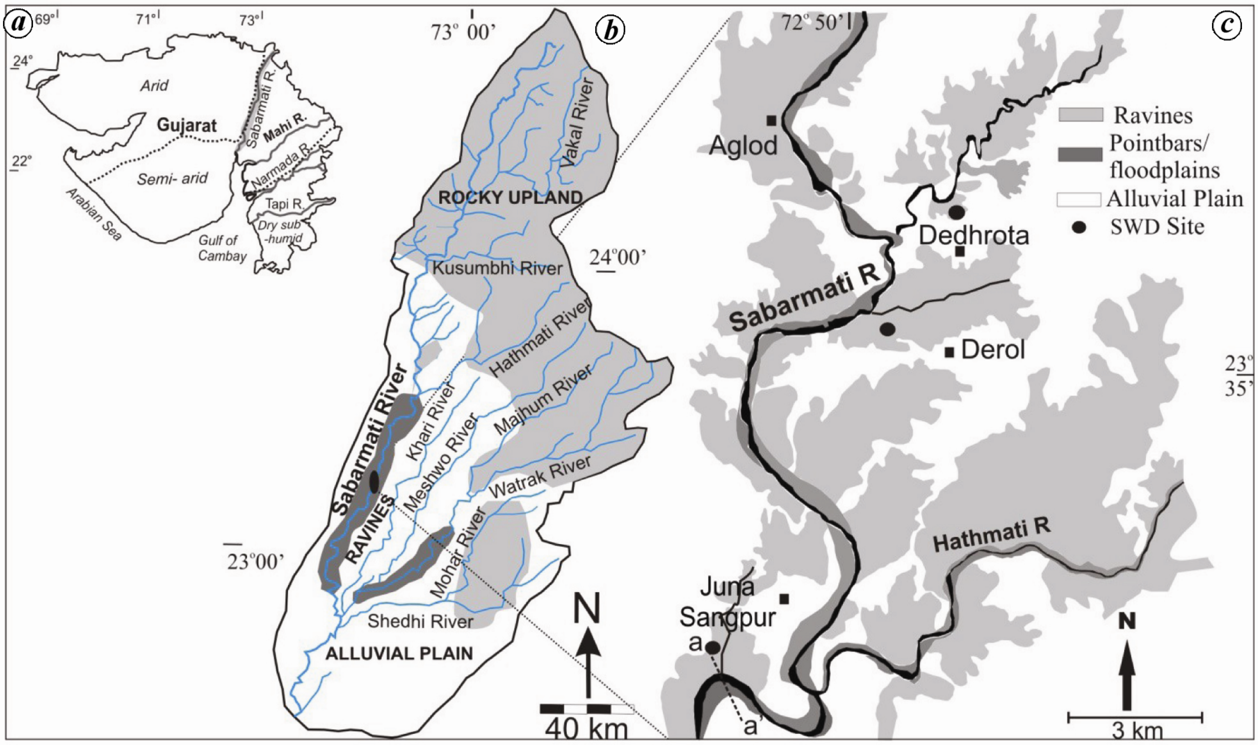

Figure 1. ***a***, Map showing the location of Sabarmati River in the semi-arid climatic zone of Gujarat. ***b***, Major geomorphic units and drainage in the Sabarmati River Basin. ***c***, Geomorphic map of the study reach showing the location of the slackwater deposit (SWD) sites within the ravines.

of slope wash and/or tributary alluvium. The hydrological parameters for reconstruction of the palaeoflood peak stage and discharge were acquired during fieldwork by profiling in association with the Survey of India topographic map and estimations were made for SWD at Juna Sangpur. The width of the present-day channel at this site is 680 m and cross-section area is 3320 m^2 (Figure 2). The minimum peak discharges of the palaeoflood were calculated using the slope–area method based on Mannings equation, $Q = 1/n(AR^{2/3}S^{1/2})$, where n is Mannings' n (index of the roughness of the stream bed), A the cross-sectional area of the stream at the flood stage, R the hydraulic radius (the ratio of the cross-section area (A) of the stream to its wetted perimeter, which is the cross-sectional distance along the stream bed and banks that is in contact with the water), and S is the hydraulic gradient[17].

At Dedhrota, a 4 m section is exposed in a stream cutting, 200 m inland from the main Sabarmati channel (Figure 1c). The stratigraphic units comprise two cycles of fine gravel and sand (50 cm; vfs – 75%, silt – 10% and clay – 15%) overlain by laminated clayey silt (60 cm; vfs – 26%, silt – 43% and clay – 31%; Figure 3). The gravel units show fine laminations and weak cross-stratifications probably deposited by the stream during monsoon flow. The intervening finer facies units comprise yellow laminated/massive silt layers and dark brown clayey silt with blocky structure. These units characterize the SWD deposited by the back flooding resulting from high-magnitude flood events in the Sabarmati. At Derol, a 1.6 m section is exposed in a nala cutting, 150 m inland and the topmost unit is at an elevation of about 15 m from the channel bed. A total of five stratigraphic units can be demarcated; two SWD units separated by loose, fine sand units. The SWD units comprise distinctly laminated, fine micaceous silt (vfs – 50%, silt – 20% and clay – 30%) capped by clayey bands with block structures. The intervening loose, massive sand (vfs – 64%, silt – 20% and clay – 20%) units also have disseminated mud balls and calcrete nodules. The profile at Juna Sangpur (Figures 1 *b* and 3) was studied in detail. AMS (accelerator mass spectrometry) radiocarbon (^{14}C) date from the soil organic carbon (SOC) of SWD unit 2 was obtained from Beta Analytics (USA).

The SWD occupy a wide area here in the ravines cut into the Pleistocene sediments (Figure 1 *c*). The top of the SWD is ~12 m above the river bed at the highest section and ~150 m inland from the present river bank. The lithostratigraphic units in the profile at Juna Sangpur include (i) 0–55 cm: massive, compact, yellow, fine sand with very fine calcrete nodules occurring in pockets (vfs – 92%, silt – 6% and clay – 2%); (ii) 55–160 cm: a set of three SWD units, very fine, massive micaceous sand, laminated silt with clay cap, blocky structure (vfs – 40%, silt – 45% and clay – 15%); (iii) 160–230 cm: slope

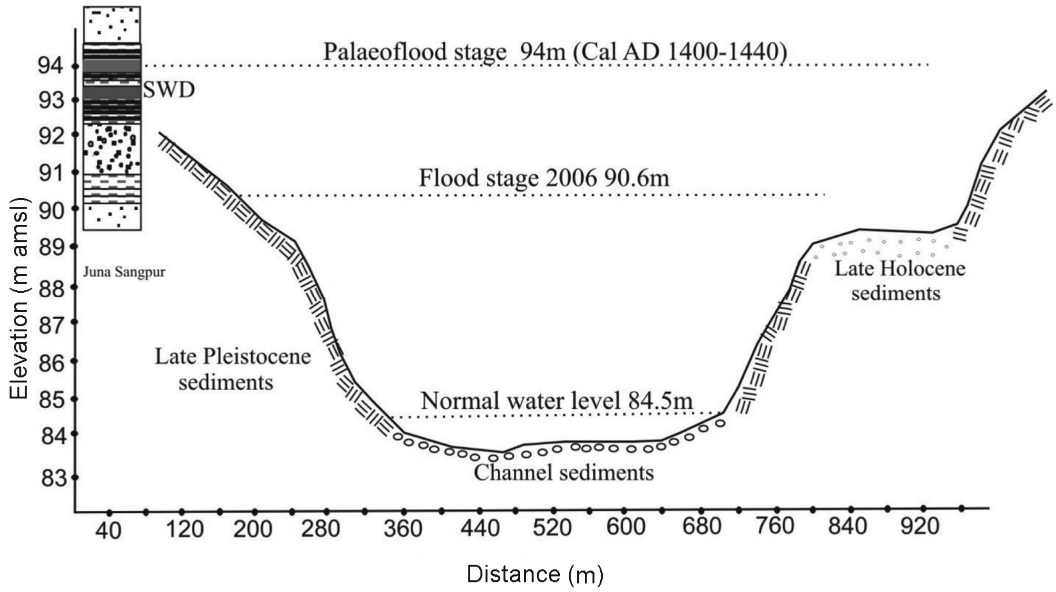

Figure 2. Channel section along *a–a′* (see Figure 1 *c*) indicating the flood stage during the recent high-magnitude flood event in 2006 and the palaeoflood event (cal AD 1400–1440).

wash sediments, coarse to medium sand with calcrete nodules; (iv) 230–260 cm: SWD units, very fine massive sand, dark brown silty clay, blocky structure. Two episodes of palaeoflood deposition, viz. unit 2 and unit 4 are separated by periods of slope wash deposition from the adjacent late Pleistocene sediment cliffs. The SOC from sediments of unit 2 has been dated to cal AD 1400–1440 (cal BP 550–510), suggesting that a flood event occurred during this period. The peak discharge estimations for SWD at Juna Sangpur using slope–area method suggest a minimum discharge of 15,680 m^3s^{-1} related to this event. Based on the present-day channel geometry, a peak flood discharge of 7303 m^3s^{-1} has been estimated for the present-day flood levels. The available gauge since 1989 has recorded maximum peak flows of 10,365 m^3s^{-1} at Gandhinagar, downstream of the study area in 1993, whereas a peak flood discharge of 8800 m^3s^{-1} at Ahmedabad, 4507 m^3s^{-1} at Kheda (both downstream) and 3050 m^3s^{-1} at Derol Bridge (upstream) has been recorded[8] during the most recent high flood in 2006. Based on these values, it can be inferred that palaeoflood event at cal AD 1400–1440 was of a much higher magnitude. The stratigraphic records suggest that one phase of flooding also occurred prior to cal AD 1400–1440 with lower magnitude than the succeeding event.

The study reveals that contrary to the present-day conditions, the Sabarmati River has experienced high-magnitude floods in the past. A history of high-magnitude floods with much higher peak discharges than the largest floods recorded in 1973 and 2006 is seen preserved in the sediment archives of the basin. The recurrence interval of such large floods is not apparent at this stage and needs further chronology of the slackwater sediments. However, it is important that any developmental activities being carried out along this river are done with due consideration of these extreme events that have occurred as close as 500 yrs BP. It is noteworthy that similar trends in flooding pattern have also been observed in the adjacent river basins in Gujarat. Two phases of high-magnitude floods 519 ± 43a and 288 ± 27a have been documented from SWD in the upper reaches of the Mahi River Basin[18] and a mega flood event with discharge ~7300 m^3s^{-1} from the middle reaches of the Mahi River Basin has been reported during the late Medieval time (14th to early 15th century) based on the pottery available from the deposits[3]. Similarly, two extreme events dated 460 ± 65 cal BP and 680 ± 50 cal BP have also been documented in the lower reaches of the Narmada[19]. The palaeoflood record spanning 800 years in the Luni River, located to the north of the study area, also shows similar clustering between 1000 and 500 years of high floods[20]. The palaeoflood records from some peninsular rivers as well as the upper Ganga catchment have revealed clustering of extreme rain events in the recent past; high flood frequency between AD 1000 and 1300, and the absence of extreme floods during the late Medieval Warm and Little Ice Age (AD 1300–1850) are linked to the monsoonal variations[21,22]. However, the available date on the flood deposit from the present study suggests the occurrence of large-magnitude flood ~cal AD 1440 in the Sabarmati River Basin. Large flood events ~AD 1490 in the Narmada Basin[9] and ~AD 1430 in the Mahi Basin[18] have been earlier reported. These are synchronous with the time-frame of the Medieval Warm Period that was an interval of strong SW monsoon[23–25]. Therefore these flood events may be linked to this phase of strengthened

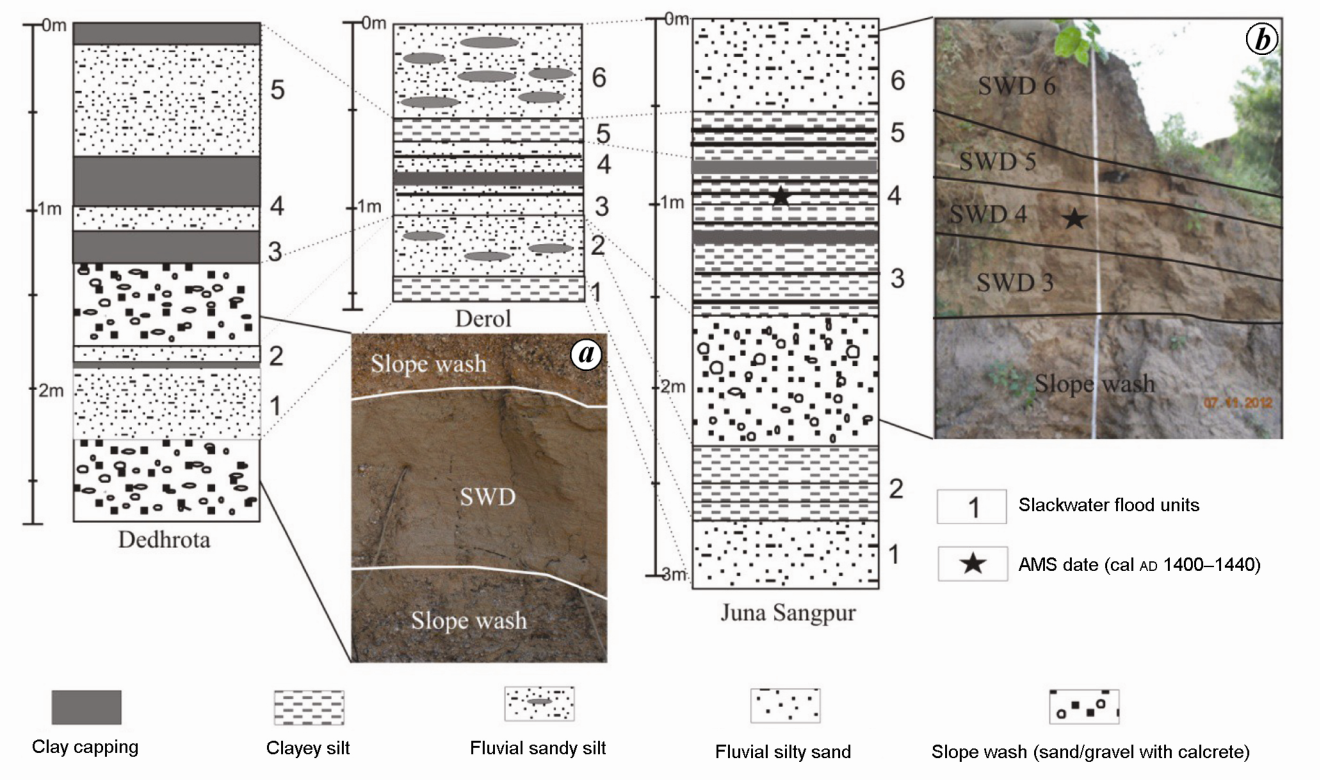

Figure 3. Lithologs of the three measured trench sections at Dedhrota, Derol and Juna Sangpur. The Juna Sangpur section is downstream of Derol and Dedhrota sections as seen in Figure 1 *c*. Note the SWD unit dated by AMS in the Juna Sangpur section. (Inset ***a***) Closeup view of SWD at Dedhrota between units of slope wash sediments at the bottom as well as the top. (Inset ***b***) Section at Juna Sangpur where six SWD units have been identified. These units have been broadly correlated in all the three sections.

monsoon. It can be further inferred that whereas the peninsular rivers[21] and the upper Ganga catchment[22] show an absence of large floods during the later part of the Medieval Warm Period, extreme flooding events probably continued to occur in the river basins in the alluvial plains of Gujarat. However, a detailed chronology of the flood records identified in the Sabarmati as well as the adjacent river basins is required before definitive inferences can be drawn on the linkages between flood magnitude and frequency in response to the regional climatic events across river basins and climatic zones.

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Recent changes in coastal configuration of Henry's Island

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The swampy intertidal zone and part of the backshore of Henry's Island coast of 1969 have now been submerged. Topographic surveys, analysis of textural and palynological character of sediments coupled with time-series analysis of shoreline change show phase-wise erosion. This has resulted in ingression of sea. Modern sands, transported from near coastal seabed, are being deposited over the ancient clayey silt bed depending on retreat of high water line and relief. The shoreline has been retreated by about 450 m to 1 km. Pollen of *Liliceae*, *Pteris*, *Microthyriod*, *Excoecaria* and *Rhizophora* in the subsurface sediments indicate the swampy nature of the earlier coast.

Keywords: Erosion, palynology, relief, shoreline change, sedimentation.

THE coast of Henry's Island, West Bengal, extending from Saptamukhi River in the east to Bakkhali River in the west, is about 3 km along north-northeast to south-southwest trend. Both the Saptamukhi River and Bakkhali River are tidal creeks only and do not discharge considerable amount of freshwater and sediment. The Island is part of the Hugli estuarine system and characterized by semidiurnal meso- to macro-tidal environment. Numerous tidal creeks have dissected the land mass into many smaller islands. There existed a low energy, swampy intertidal zone in 1969 and there was dense forest in the backshore area (SOI toposheet) with clayey silt sediment cover. The present study reveals that the erstwhile coast as well as part of the backshore have now been submerged. Modern sands are being deposited over the ancient clayey silt sediment transforming the swampy intertidal zone into a sandy beach.

This area is almost unchartered. Not much information is available regarding the river discharge and sediment load. The sediments are being deposited on the coast from the near coastal seabed by tidal water after primarily being discharged by the Ganga River system into the Bay of Bengal[1]. There is no direct input on the coast from the river as such. The present study aims to understand the changes in coastal configuration pattern over the last 40 years.

Detailed field work and beach profiling have been carried out along the coast of Henry's Island during 2011–12 to study the geomorphic features and sediment character of the area. High water line (HWL) has been demarcated. Topographic survey and beach profiling have been done with the help of theodolite and auto level along nine transacts perpendicular to the coastline with an interval of about 300–500 m between the profiles. The interval of the profiles was drawn depending upon the geomorphic features. The survey was done from about 0.5 m water depth up to 1 km landward. In some sectors, surveying was restricted to less than 1 km due to inaccessibility. Profiling has been done connecting R.L. from the benchmark (2.6 m; toposheet no. 79C/6, 1969) of Irrigation Inspection Bungalow, Frasergunj. The beach profiling in 2011 has been done to measure the relief and slope of the present coast and also to delineate different units on the present coast vis-à-vis its relief. The topography of the coast has been visualized with the help of relief data. The topographic features along with sediment

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