Causation and avoidance of catastrophic flooding along the Indus River, Pakistan

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ABSTRACT

The catastrophic flood of 2010 along the Indus River began in July with unusually intense but not unprecedented rainfall in the upland catchment. During four months, close to 2,000 fatalities occurred and ~20,000,000 inhabitants were displaced. The meteorological events triggered but did not cause this "natural" disaster. Analysis of multi-temporal remote sensing and topography instead indicates that most damage was caused by dam and barrage-related backwater effects, reduced water and sediment conveyance capacity, and multiple failures of irrigation system levees. The numerous failures extended from upstream areas, where some record discharges occurred, to downstream reaches and the delta, where peak discharges were not extreme. In Sindh, Pakistan, two major river avulsions (sudden changes in flow location) occurred. At one of these (the northern avulsion), Indus water flooded ~8,000 km^2 of agricultural land to depths of 1–3 m; part of the river flowed 50–100 km west of its pre-flood location. The avulsion was caused by breaching of the Tori Bund, an artificial levee upstream of Sukkur Barrage, on 6–7 August, two days before arrival of the first flood crest and long before attainment of peak river flow at Chacharan, 100 km upstream, on 24 August. The early breach, during the rising stages of the flood, permitted much of the incoming flood wave to feed the avulsion over a sustained period.

As was the case for the dramatic and temporary avulsion of the Kosi River, India, in 2008, the lack of planned accommodation to the river's high sediment load and its super-elevation above the surrounding terrain set the stage for exceptionally dangerous levee failures and channel avulsions. Major translocations of river flow will continue to occur during large flood events whether flood warning is improved or not. The observed dynamics indicate that reinforcing the existing engineering structures is not a sustainable strategy for avoiding future flood catastrophes. Instead, planning for major water and sediment flow diversions is required for effective flood control along the Indus and other sediment-rich and avulsion-prone rivers.

INTRODUCTION

Following the Great Flood of 1993 along the Upper Mississippi River, USA, orbital remote sensing has been increasingly employed to investigate inundation dynamics (Brakenridge et al., 1994, 1998; O'Grady et al., 2011). Here, we analyze data from a suite of orbital sensors to track the 2010 Indus River flooding at high spatial resolution and frequent temporal sampling. The Shuttle Radar Topography Mission (SRTM) provides topography at 90 m spatial and ~1.3 m vertical resolution; the data were collected in February 2000, during the dry season when the Indus River was at an extreme low stage (Digital Elevation Model [DEM]; see GSA Supplemental Data[1]). GeoEye data show surface water changes finer than 1 m; the MODIS sensor revisits twice daily at much coarser spatial resolution and AMSR-E provides independent monitoring of river discharge changes. The analysis demonstrates why the 2010 Indus River flood was catastrophic and what approach must be taken to avoid future flood disasters along this and other rivers in similar geological settings.

HYDROMETEOROLOGICAL CONTEXT OF THE 2010 FLOOD

The Pakistan flooding, July–November 2010 (DFO event 3696) caused close to 2000 fatalities, displaced 20,000,000 inhabitants for weeks to many months, and was 7.5 on a duration–area affected–intensity scale that compares flood magnitudes on a global basis (Chorynski et al., 2012; Brakenridge, 2012). Flooding along the Indus River began in mid- to late July following unusually heavy monsoonal rain in northern Pakistan and was sustained in downstream areas through the end of 2010 (Fig. 1). Exceptional damage was inflicted on crops and cropland and on agriculture support systems such as canals and levees; 4,500,000 mainly agricultural workers lost their employment for 2010–2011 (Khan, 2011).

The Indus is monsoon-driven and Himalayan snow-fed, and drains an area of 970,000 km^2. Historically, its average coastal discharge was ~3000 m^3/s; with diversions and agricultural use, this discharge has fallen to 300 to 800 m^3/s with long periods of no flow (Asif et al., 2007). Until recently, the river carried very high sediment loads to the sea, but dams and diversions have reduced coastal delivery by 10 times (Milliman and Syvitski, 1992). Entering Sindh Province from the north, a meandering channel is constrained within the 15- to 20-km-wide floodplain by engineered artificial levees or "bunds" (Fig. 1). Bordering both sides of this modern floodplain lie the >200-km-wide "historical floodplain" lands that have experienced prior changes in the location of the channel and meander belt. Thus, except far upstream, the Indus River flows through a 5 Ma alluvial landscape of its own making (Clift and Blusztajn, 2005; Giosan et al., 2012). The ongoing sedimentary and erosional processes are mediated by the basin's monsoon- and

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[1] GSA Supplemental Data Item 2013073, precipitation data, flood inundation chronology, river discharge, and digital elevation model, is online at www.geosociety.org/pubs/ft2013.htm. You can also request a copy from GSA Today, P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

snowmelt-driven hydrometeorology and by continuing uplift of the Himalayan orogen, forming its highest topography to the north, and by sediment compaction and subsidence downstream and in the delta.

Some aspects of the 2010 monsoonal rains were unusual (Houze et al., 2011). July–August precipitation totals were above average but not exceptional for Pakistan as a whole (Precipitation; see GSA Supplemental Data [footnote 1]). However, northern Pakistan rainfall rates during monsoon storms were extreme compared to 1998–2010, and there were unusually frequent downpours (Webster et al., 2011). The Supreme Court Inquiry Commission report notes: “Beginning 27th July, an unusual convergence of easterly NW system was noted over north western Pakistan … with westerly Arabian sub-tropical winds forming a static jet for almost 48 hours. … By 30th July rains had generated raging floods” (Khan, 2011, p. 85). The Khyber-Pakhtunkhwa region, far upstream along the Indus, experienced unusually high rainfall totals: >300 mm for 27–30 July (Supplemental Data Fig. S1). The Punjab, Gilgit Baltistan, and Azad Kashmir provinces that commonly receive monsoon deluges include stations with July 2010 rainfall totals of >500 mm. Pakistan-wide August rainfall totals were 75% of July totals. The flood wave then moved downstream into drier areas during the months-long catastrophe: Sindh Province suffered the worst of the flooding but received relatively little rainfall throughout the monsoon. The downstream regions had weeks of advance notice of the expected high Indus discharges, yet exceptionally high damage still occurred.

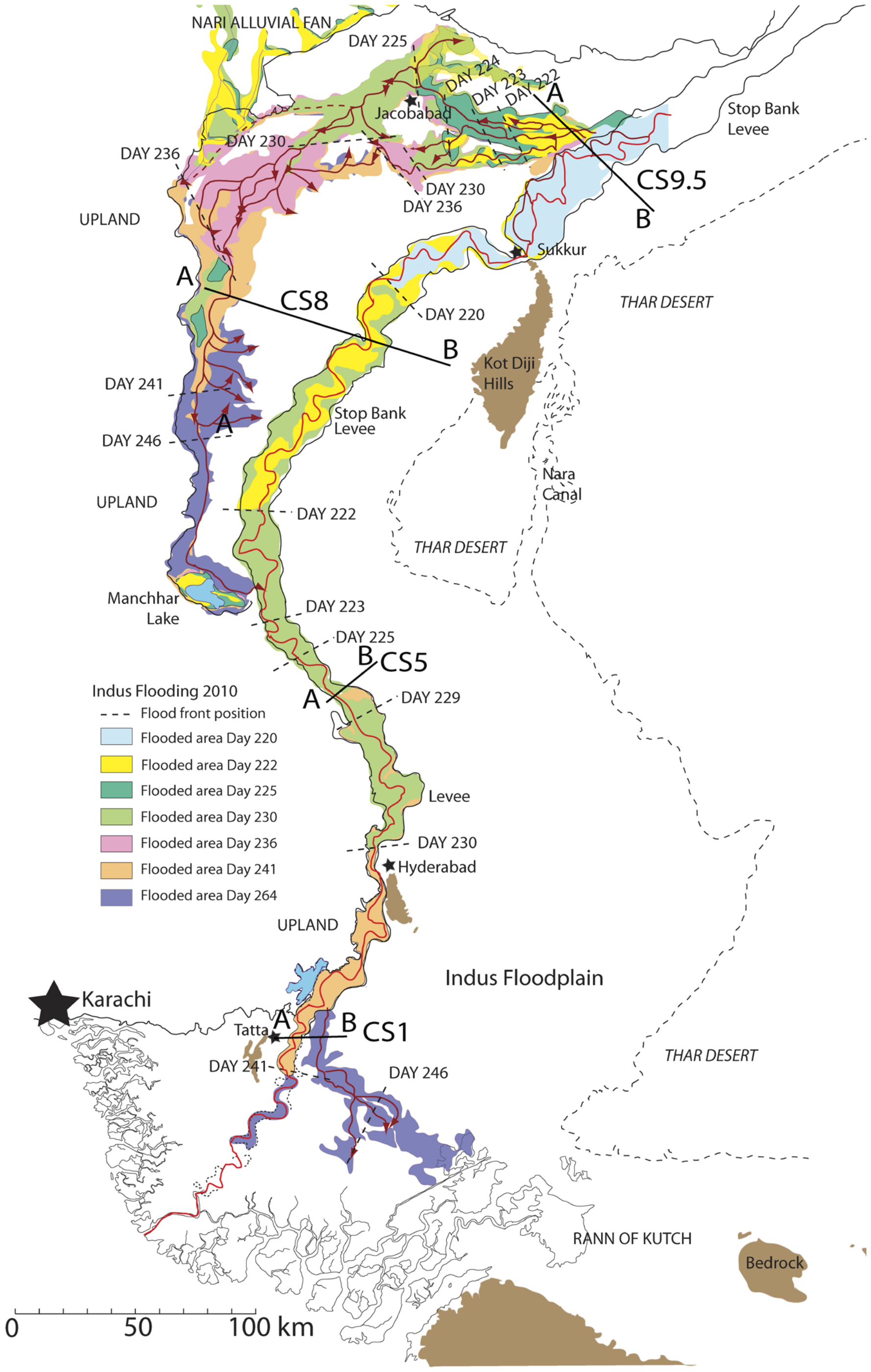

Figure 1. Summary map showing the progress of the 2010 Indus flood wave and its two main avulsions, key features, and towns. Arrows show the direction of overbank floodwater as determined by progressive inundation from the remote sensing data (see Flood Inundation and Chronology, GSA Supplemental Data [text footnote 1]). Day 222 is 10 August 2010. See Figure 3 for data on profiles CS1, CS5, CS8, and CS9.5.

The flood involved the Indus River and its tributaries Jhelum and Chenab. At four sites along the lower portions of the river, in Sindh, Punjab, and Balochistan, we use passive microwave remote sensing calibrated by hydrological modeling to estimate peak discharges and measure their times of arrival (Supplemental Data Figs. S5 and S6). The peak flows were larger than other, similarly measured twenty-first–century floods (period of record 2002–2010) but not exceptional compared to late twentieth-century events. Thus, upstream at Guddu Barrage, estimated peak flows of 33,970 m^3/s occurred on 15 August 1976; 33,200 m^3/s on 13 August 1986; and 32,920 m^3/s on 31 July 1988. At Sukkur Barrage, downstream, estimated peak flows of 33,030 m^3/s are recorded for 15 August 1986; 32,880 m^3/s in 1976; and 31,680 m^3/s for 31 July 1988 (Akhtar, 2011). These compare with the ground-based estimates for 2010 at Guddu of 32,530 m^3/s on 8–9 August, and at Sukkur of ~32,000 m^3/s on 9–11 August for peak flow (Government of Pakistan, 2011, p. 28). Flow lost at upstream breaches is, in both cases, not included.

According to our independent estimates, the flood wave crested ~100 km upstream at Chacharan (site 2009; Supplemental Data Fig. S6B) at 35,000 m^3/s on 24 August. Meanwhile, the discharge at Ghauspur (site 2008; Fig. S6a) never

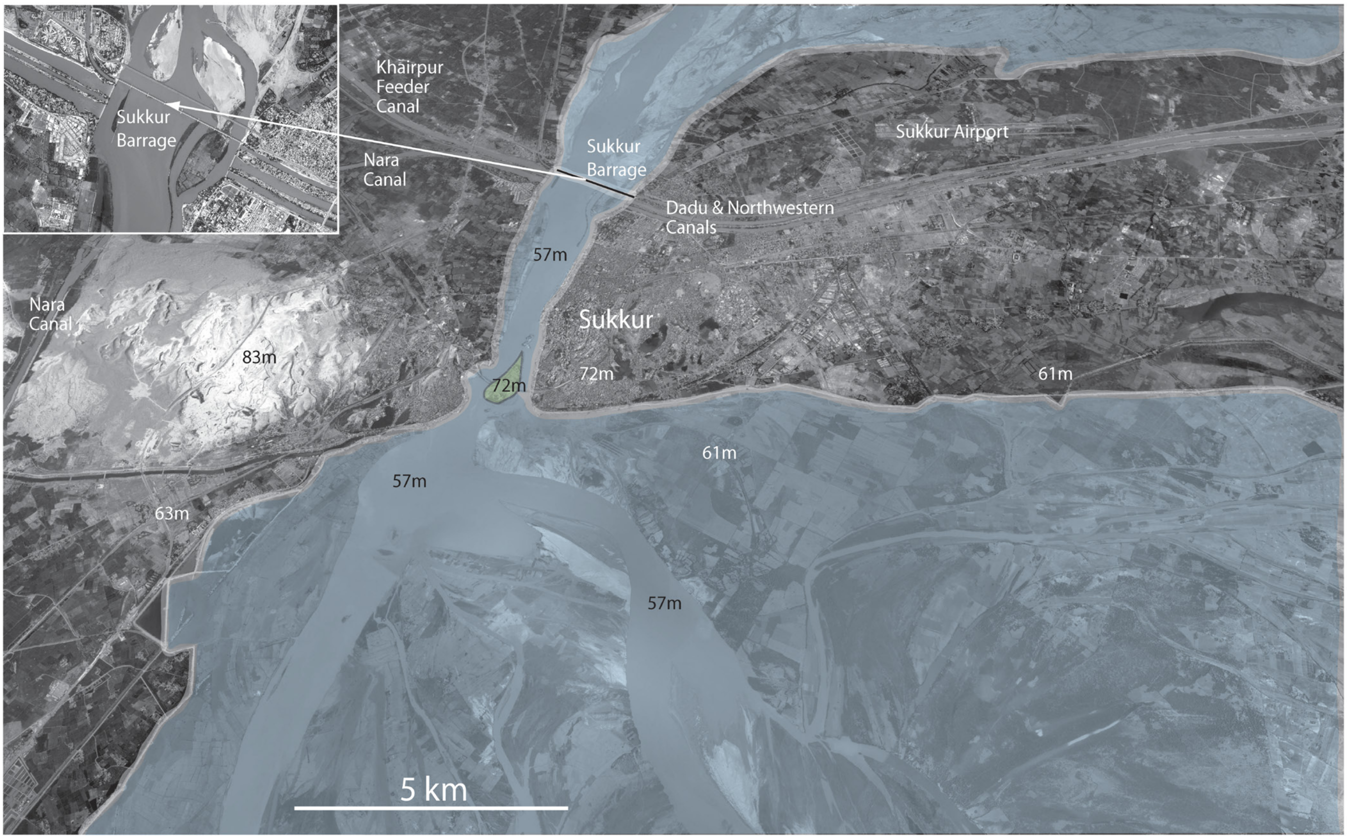

Figure 2. The modern Indus floodplain (south is top; west is right) facing the town of Sukkur, which is situated on a bedrock surface 10 to 15 m above the locally confined river channel. The Sukkur Barrage diverts up to 50% of the Indus discharge via a series of feeder cannels (Nara, Khaipur, Dadu, Northwestern). On this ASTER image, the 2010 floodwaters are shown in transparent gray, contained by stop banks outlining the modern Indus floodplain. The narrow constraint of the natural mini-gorge together with the barrage causes advancing floodwaters to slow and rise upstream (bottom of image), thus increasing local sediment aggradation.

exceeded 25,000 m^3/s, due to the breaching of nearby levees, including the Tori Bund on 6–7 August, and the diversion of ~7000 m^3/s onto the surrounding agricultural lands (Fig. 1). Levee breaching began at only ~20,000 m^3/s, a level reached every few years; levee overtopping was not the primary cause (Khan, 2011, p. 16). This "northern avulsion" (described in the following section) near the city of Sukkur occurred 17 days before peak of flooding upstream at site 2009. By the time of arrival of the flood crest, the northern avulsion breach had already been scoured to a depth allowing direct access to the river (Flood Inundation Chronology, Supplemental Data).

Our remote sensing findings agree with depositions to the Pakistan Supreme Court during its investigation of the flood: "In essence, he deposed that in record high 1976 floods, 1.2 million cusecs (33,980 m^3/s) of water passed Indus at Guddu Barrage without breaching Tori Bund; in 1996, only 500,000–600,000 cusecs (14,158 m^3/s–16,990 m^3/s) caused it to breach, that was repeated during 2010" (Khan, 2011, p. 34). Also, the Annual Report of Pakistan's Federal Flood Commission states that exceptionally high flows began entering Guddu Barrage, upstream of the Tori Bund, on 5 August, that the first high peak of this flood event occurred at Guddu on 8–9 August, and that it arrived at Sukkur Barrage on 9–11 August (Government of Pakistan, 2011, p. 34–35).

It is also clear that the relevant government ministries did not have adequate information as they attempted to respond: "Actual arrivals on 7/8th August of 1,148,700 cusecs (32,528 m^3/s) at Guddu Barrage far exceeded the formulae-based departmental projections of 850,000 cusecs (24,070 m^3/s). By then, the Tori Bund breach was already allowing a new course for the flooding Indus far to the west. This avulsion was afterward fed by continuing rising floodwater, including a new peak traversing between Guddu and Sukkur 14–17 August" (Government of Pakistan, 2011, p. 36). Breaching of the downstream Aliwahan levee, on the east bank, did not occur (this levee had been purposefully breached during the 1976 flooding); pressure on the Aliwahan levee must have been reduced by the Tori breach. In the course of this large flood event, the only downstream damage mitigation possible was spilling of excess floodwater upstream.

NON-METEOROLOGICAL CAUSES OF THE DISASTER

We offer here a geomorphological perspective on this flood catastrophe. The remote sensing data (Flood Inundation Chronology, GSA Supplemental Data [footnote 1]) agree with many of the findings reached by in-country water ministries (Khan, 2011), and this information does not support exceptional weather phenomena as the principal cause of the catastrophe. Levee failures led to the northern avulsion (Figs. 1–3), including in particular the 2.7 km break at the Tori Bund. The bund was in poor repair, had failed repeatedly in prior floods, by 2010 had lost 1.7 m from its design height due to erosion and poor maintenance,

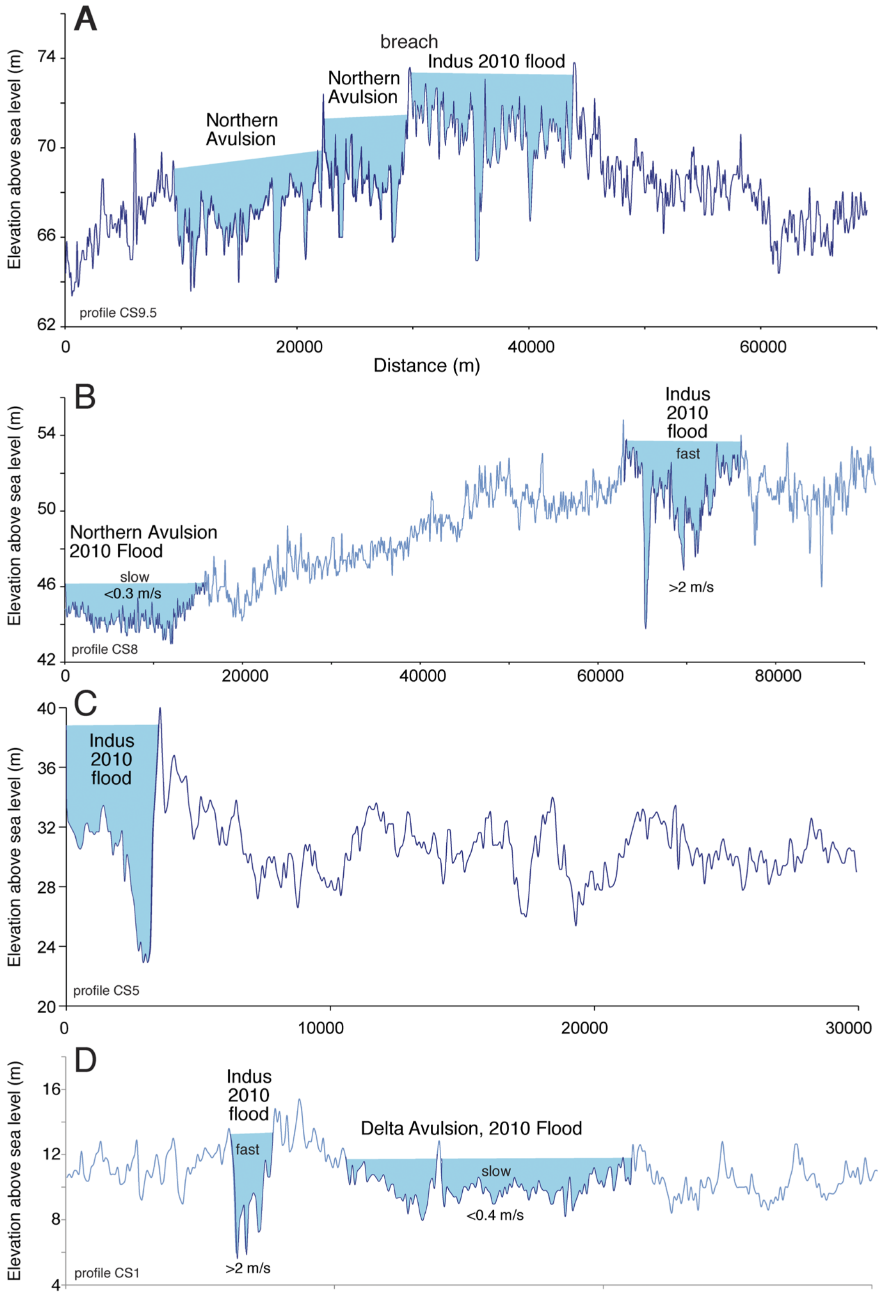

Figure 3. Four SRTM-based topographic sections across the Sindh portion of the Indus floodplain (see Fig. 1 for their locations) showing the maximum 2010 flood heights in blue. Note the different scales for each profile. (A) The backwater-elevated flood waters of the Indus and the northern avulsion breach location. (B) The super-elevated Indus floodplain, above the slower moving northern avulsion floodwaters. (C) Indus floodwaters contained by the levee stop banks. (D) The river flowing quickly beside the slower moving southern (delta) avulsion.

and was breached in advance of flood crest arrival. Attempts to repair the failures during the flood involved local removal of more levee height to fill pits developed in the riverward side of the levee (6–7 August). As the flood wave reached this location, its failure, and river avulsion to the west (Figs. 1, 4A, and 4C; Supplemental Data Figs. S2, S3, and S4) captured a significant portion of the Indus flow, causing "extensive damage … and further breaches to the Shahi and Begari canal systems … many lives were lost and extensive property was destroyed or sub-merged in Naseerabad Division. Jaffarabad District was completely inundated … floods swept away vast cropped areas leading to declaration of emergency on 14–15 August." In all, 1,315,342 people in four districts, including those from Sindh, were directly exposed to the Tori breach, and 97 deaths were reported (Khan, 2011).

Although it directly caused much of the extreme damage, the northern avulsion was not itself a rare event. All major floods along this river have been accompanied by breaches of the levee system and spilling of flood water (Asif et al., 2007; Mustafa and Rathall, 2011). Many breaches have been intentional: The diversion of excess discharge onto agricultural lands in order to protect cities and engineering structures was a standard flood control approach when the area was under British colonial rule (Mustafa and Rathall, 2011). The Tori Bund failed in 1904, 1930, 1932, 1942, 1975, 1976, and 1995 (Khan, 2011); each time, it was rebuilt. The vulnerability of the control structure at this location was known, and its upgrade and repair had been urgently recommended but was not accomplished (Khan, 2011). Its breaching before arrival of the 2010 flood crest is testimony to the critical geomorphological context of flood catastrophes along this river. Tori Bund is an example of a systemic problem. The proximate cause for this flood disaster was the intersection of (1) a suite of ongoing, non-stochastic, and relatively predictable depositional mechanisms exhibited by a confined, sediment-rich river flowing on an alluvial ridge; and (2) the lack of explicit engineering and societal accommodation to these natural geomorphological processes.

IMPORTANCE OF RIVER AVULSION

Of these processes, the potential for avulsion is of most concern. Avulsion (Slingerland and Smith, 2003) is not limited to very restricted reaches of the river, but structural modifications and valley geomorphology may help locate where it occurs and how it affects flood hydrology. For example, downstream of the northern avulsion breach, Indus floodwaters pass through a natural mini-gorge where the Sukkur Barrage, controlling one of the largest irrigation projects in the world, diverts Indus water into feeder canals (Fig. 1). This narrow constraint slowed the floodwaters, caused backwater stage increases upstream (an area of local sediment aggradation; Fig. S3, GSA Supplemental Data [footnote 1]), and helped to localize this breach. The next downstream monitoring station (Hala; site 2010: Fig. 4C; Supplemental Data Fig. S5B) shows the flood-wave cresting at ~24,000 m^3/s on 24 August and again on 9 September at ~24,500 m^3/s, after northern avulsion floodwaters rejoined the Indus (Fig. 4).

On 27 August, a second major levee breach occurred along the southeast bank of the Indus, far downstream in southern Pakistan near Daro. It occurred at a location that had previously experienced similar changes through recent history and prehistory (Holmes, 1968; Wilhelmy, 1969). Approximately 10,000 m^3/s were diverted into a "delta avulsion" (Figs. 1–3) such that at site 2011 (Kotri Allahrakhio), south of that breach, discharge never exceeded ~15,000 m^3/s (Fig. 4D; Supplemental Data Fig. S5A). By 1 September, the delta avulsion had advanced 45 km, flooding the town of Sujawal; however, it lessened the severity of flooding further south in Thatta (see also Erosion and Other Impacts, Supplemental Data).

Similar changes are documented along other sediment-rich rivers (Kale, 2008) and are an inherent feature of such fluvial systems. Avulsion is distinct from crevassing (Slingerland and Smith, 1998), in which levees may be breached or overtopped, floodplains are temporarily occupied by flood water, and coarser overbank deposits are superimposed over finer sediment. Instead, river avulsion may be permanent without human intervention, and the translocation is not confined to the existing meander belt. It is at least a two-step process: (1) sedimentation along a relatively fixed channel bed, over many years of time, elevates such above surrounding terrain (for the Indus, see Supplemental Data Fig. S8); and (2) during floods, breaches in banks and levees allow major shifts of the position of the channel and its meander belt to a new, lower, location, perhaps hundreds of kilometers distant (Figs. 1 and 2). Decades may be required to accomplish a complete avulsion, with repeated floods scouring deeply enough to create a persisting new river channel. Alternatively, the new location may be immediately occupied.

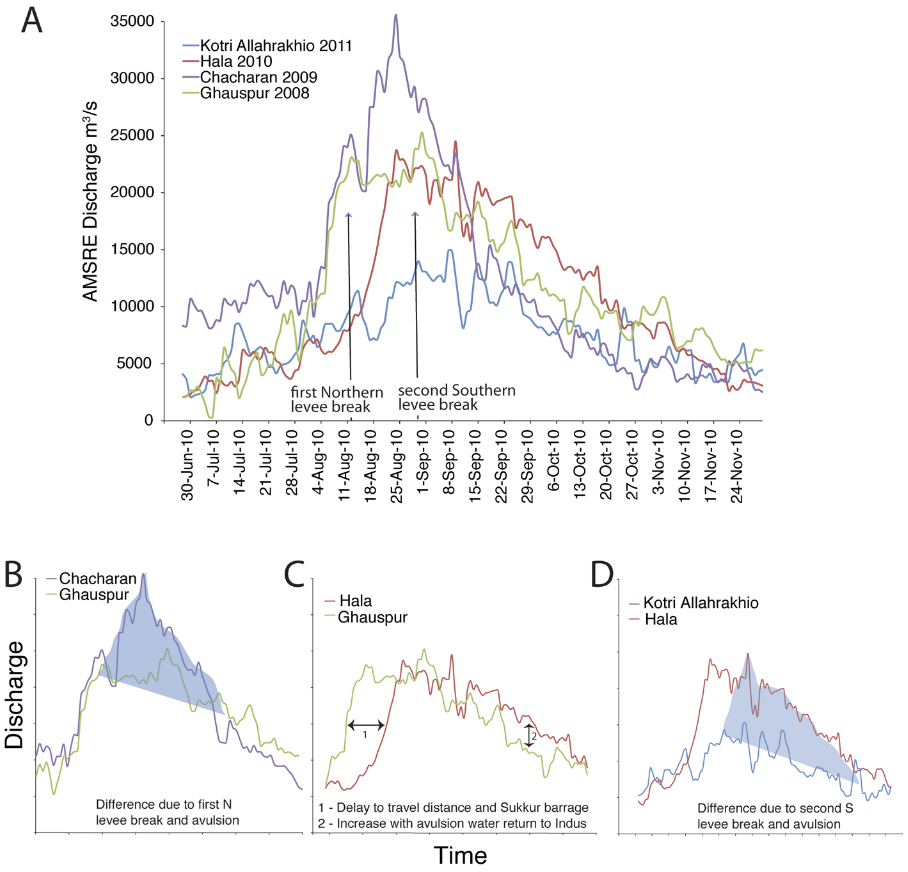

Figure 4. Analysis of the timing and magnitude of the 2010 Indus flood wave at the river measurement sites (see Fig. 1 for locations). (A) Satellite microwave river discharge estimates (see also GSA Supplemental Data Figs. S5 and S6 [text footnote 1]) of the 2010 flood and the northern and delta avulsion levee breaks. The lower figures show detail: (B) Indus flood wave at Chacharan and at Ghauspur just downstream of the northern avulsion point; the magnitude difference is from missing avulsion discharge (see Supplemental Data Fig. S7); (C) between Ghauspur and downstream Hala, located seaward of Lake Manchar; and (D) between Hala and Kotri Allahrakhio, located downstream of the delta avulsion.

Studies of other river avulsions indicate the importance of local conditions, including floodplain sedimentology and previously occupied channels, in determining the change (Aslan et al., 2005; Jones et al., 1999; Slingerland and Smith, 1998; Törnqvist and Bridge, 2006). Previous major avulsions of the Indus are documented in history and prehistory, including a river position at B.C. 300 closely similar to that temporarily occupied after the northern avulsion in 2010 (Holmes, 1968; Wilhelmy, 1969). The recent avulsion of the Kosi River in Bihar, India (Kale, 2008), is also a useful comparison. On 18 August 2008, 80%–85% of the Kosi water discharge shifted by ~120 km after a levee failed at Kusaha, Nepal, 12 km upstream of the Kosi barrage (Sinha, 2009). The event was the latest of a series along this river (Wells and Dorr, 1987), where even a small flood can trigger an avulsion at sensitive locations (Jones et al., 1999; Sinha, 2009). Long-abandoned Kosi channels may be reoccupied, or new ones carved. As can be the case for the Indus, the 2008 Kosi avulsion occurred during a common high discharge that was less than the design capacity of the engineered levee system (Sinha, 2009). Avulsion to the east occurred even though twentieth- and twenty-first–century aggradation was preferentially on the east: The overall channel is raised compared to adjoining land on both sides, and the structures designed to protect from flooding set the stage for a disastrous event by confining channel and channel-marginal sedimentation to one location over long periods of time (Sinha, 2009). The Kosi avulsion in 2008 caused >400 fatalities and displaced 10,000,000 people (Brakenridge, 2012).

Events somewhat similar to this occurred along the Sindh portion of the Indus in 2010, where the Indus flows along the crest of a convex-upward, ~ 10–15-m-high, ~ 100-km-wide alluvial "mega-ridge" (Giosan et al., 2012; also see Fig. 3 and Digital Elevation Model, Supplemental Data). After the breach at the Tori Bund, 22% of the river flow was diverted from the main channel for 37 days. During its occurrence, the avulsion path widened and developed with many merges and splits (Fig. 1). The avulsion progressed down-valley at an average speed of 10 km/d (0.1–0.3 m/s), occasionally becoming delayed at irrigation canal levees and roads. In contrast, the flood wave within the preexisting channel and stop banks traveled at three times this rate. Even after the Indus River no longer fed the northern avulsion (post–1 Oct.), the southerly parts of the avulsion continued to expand, as driven by the topographic gradient and without being confined or channelized by any planned spillway. Indus River water flooded ~8000 km^2 of agricultural land 50 to 100 km west of the pre-flood river, typically to depths of 1 to 3 m (Fig. 3), along a 354 km travel route (Flood Inundation and Chronology, Supplemental Data). Thus, the extensive damage caused by the avulsions was associated not only with the incoming flood wave and insufficiently strong and maintained levees, but also with the lack of planned spillways—even at sites where breaches were artificially created in the past. Along both the Indus and the Kosi, engineered spillways could have channeled the escaping floodwater, greatly restricted the geographic extent of inundation, and facilitated early warning of the population in danger.

CONCLUSION

The 2010 Indus flood inundated nearly 40,000 km^2, was exceptionally lethal, caused massive displacement of the population, severely damaged Pakistan's national economy, and nearly depleted the resources of international disaster responders. Remote sensing of this catastrophic flood demonstrates that much damage was directly caused by two river avulsions—the first of which occurred before the flood crest reached the avulsion site. Given the tendency for avulsion, individual levee reconstruction is unlikely to enhance overall flood protection and instead may worsen the risk (any failure of higher levees will be even more catastrophic, and if upstream levees do hold, downstream discharges are increased). Reconstruction of past channel location and the detailed sequence of events in 2010 together indicate a different need for improving flood protection. There is no single stable or equilibrium location for high-sediment load, actively aggrading rivers such as the Indus and the Kosi. Unless the engineering response changes, even modest flood events in the future will continue to pose an increasing risk of exceptional damage.

The lesson of the 2010 Indus floods is that large populations are presently at grave risk, and that it will not be long before future flooding causes similar damage. Other workers have focused on the storm events that led to the Indus flooding and on the need for better prediction of such events and modeling of the resulting flood water (Webster et al., 2011). However, improvements in this area alone will not address the continuing increase in flood risk along sediment-rich rivers such as the Indus. Instead of attempting to permanently fix the channel in its present location during large discharges, planning for temporary channel diversions to spill both water and sediment during floods is necessary. In southern Pakistan, intermittent transmission of Indus floodwater and sediment to the sea, along pathways and spillways designed to protect local populations (Kale, 2008), could also mitigate subsidence and other geological processes that are increasing vulnerability to coastal flooding caused by ongoing sediment starvation of the delta areas (Syvitski et al., 2009).

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