Supplemental Data

Causation and Avoidance of Catastrophic Flooding along the Indus River, Pakistan

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Precipitation

Data Sources: NASA's Tropical Rainfall Measuring Mission (TRMM) precipitation product is derived from Precipitation Radar, a TMI Passive Microwave Radiometer (10.7 to 85.5 GHz), and VRS Visible & Infrared Scanner. The TRMM precipitation data is combined with SSM/I data (0.5° x 0.5), low-orbit GOES IR (1°x1°, 3-hourly), TIROS Operational Vertical Sounder (1°x1°, daily), Advanced Microwave Scanning Radiometer - EOS (AMSR-E), Advanced Microwave Sounding Unit (AMSU-B), and gridded rain gauge data run through algorithm 3B-43 (Huffman et al., 2007). These 3-hourly 0.25° x 0.25° TRMM precipitation estimates were augmented by hourly ground-based rain-gauged data provided by the Pakistani Meteorological Service (http://www.pakmet.com.pk/FFD/index_files/) for 95 stations: 36 Punjab stations, 12 stations in the Gilgit Baltistan/Azad Kashmir area, 17 stations in Khyber-Pakhtunkhwa, 15 stations in Sindh province, and 15 stations in Balochistan.

Observations: The 2010 Pakistan monsoon lasted approximately 2 months, from mid-July to mid-September. This monsoon was enhanced by a La Niña phase in the tropical Pacific; the atmospheric circulation changes penetrated deeply into northwestern

Pakistan by late July. The rainfall fell in pulses, each separated by a week (Webster et al., 2011). Earlier rainfall caused flooding in Balochistan (<u>www.pakmet.com.pk</u>). Khyber-Pakhtunkhwa experienced unusually high rainfall totals compared to its normal, with stations Peshawar A/P receiving 330 mm in 2 days, Saidu Sharif receiving 330 mm in 3 days, and Cherat receiving 371 mm in 3 days (July 27-30; Figure S1). The Punjab, Gilgit Baltistan and Azad Kashmir provinces that more commonly receive monsoon deluges had stations with July rainfall totals of >500 mm. Rainfall continued to be heavy in these provinces for the first half of August. The Pakistan-wide August rainfall totals were 75% of the July totals; with September only 25% of the July values. Sindh province, which suffered the worst of the Pakistan 2010 flooding, was commonly dry throughout the 2010 monsoonal period. The high 2010 rainfall rate contributed to the Indus flooding, and as possibly abetted by the severe drought of 2009 that led to sparser 2010 vegetation cover (Webster et al., 2011). Human-related deforestation in northern Pakistan is considered severe (Ali et al., 2006).

Relation to Flooding: There are 67 reported flooding events in Pakistan since 1900 with a clustering of 52 events in the last 30 to 40 years (International Disaster Data Base, http://www.emdat.be). Some of these events (e.g., 1950, 1973, 1976, 1977, 1992, 2001, 2007 and 2008) were also accompanied by large loss of life and property. The apparent increased frequency of reported floods is consistent with the increase in global monsoon intensity accompanying the last three decades of general global warming (B. Wang et al., submitted manuscript, *Nature*, 2011) or the documented trend towards more intense monsoon rain events (Goswami et al, 2006), but reported flooding can also be amplified by a rapidly growing population and changes in water management strategies. From 1988 to at least 2008, there also occurred a substantial increase in May-September mean discharge in the upstream Indus that is attributed to higher snowmelt and also monsoon precipitation (Cook and Ahmed, 2011). Generally, July and August 2010 precipitation totals were above average in Pakistan but not exceptional. However, rainfall rates were extreme compared to other years in the 1998–2010 period.

Flood Inundation Chronology

Data Sources: NASA MODIS sensor data were used to map the evolving areal extent of the Indus 2010 flood with high temporal resolution (near-daily). The Aqua and Terra satellites fly polar orbits: Terra provides morning MODIS coverage and Aqua provides images a few hours later (early afternoon). MODIS "Rapid Response Subsets" of the area include 3-channel composites using 2.16 µm, 0.88 µm, and 0.67 µm wavelength bands, resampled to a spatial resolution of 250 m. In these standard products, clear water appears black, and water with suspended sediments appear various shades of blue depending on concentration. MODIS simulated true color imagery use the 0.67 µm, $0.56 \,\mu\text{m}$, and $0.48 \,\mu\text{m}$ wavelengths for the same subsets, and these data distinguish turbid water from water with low sediment concentrations. Cloud cover affects temporal sampling, but during the 2010 Indus flood, <5% of the days were removed by such interference. Our study also employed Dartmouth Flood Observatory (DFO) water classification and inundation mapping based on an algorithm that ingests four images (Terra and Aqua, each day, for two days) and applies a cloud shadow filter and a filling process. This takes advantage of moving cloud obscuration to increase spatial coverage (Brakenridge et al, 2012).

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The MODIS information was augmented with higher spatial resolution imaging to determine details of the flooding extent and flood damage. These data include:

- 1) Landsat 5 and 7 (<u>http://landsat.gsfc.nasa.gov/</u>) with pixels of 15 m ground dimension (0.52-0.9 μ m bandwidth), and 30 m (5 bands within the 0.45 -1.75 μ m bandwidth). The Landsat 7 ETM+ scenes of the Indus 2010 floodplain were in part affected (<25% of total area) by scan-line corrector malfunction interference.
- ASTER data (<u>http://asterweb.jpl.nasa.gov/</u>) with pixels of 15 m ground dimension (3 wavelength bands within 0.52 0.86 μm), and 30 m (6 wavelength bands within 1.6-2.43 μm).
- Geo-Eye very-high resolution, with pixels of 0.41 m ground dimension for panchromatic imagery and 1.65 m for multispectral imagery, in 15.2 km swaths (for details see <u>http://www.geoeye.com/CorpSite/</u>).

Observations: Crossing Punjab Province, the Indus is a slightly sinuous, sometimes anastamosing river (Figure S2a-c). As the river enters Sindh Province it becomes meandering across a 15 to 20 km-wide modern floodplain that is confined within engineered stop-banks and other structures (Figure S2d-f). On either side of the modern floodplain lies the historical floodplain that is more than 200 km wide. The modern floodplain is mostly super-elevated with respect to the historical floodplain. The 2010 Pakistan flood included the Indus River, and its branches the Jhelum and Chenah rivers (Figure S2a, b, c). The detailed chronology of the Sindh Province flood, our focus, is provided below: Day 212, July 31 – The main flood wave had not yet reached the city of Sukkur.

Day 213, Aug 1 – The floodwater remains channelized while passing through the Sukkur Barrage.

Days 214-219, Aug 2-7 – Cloud cover limits satellite observation.

Day 220, Aug 8 – Floodwater levels are dramatically higher along a 50 km stretch of the Indus River upstream of the Sukkur Barrage, drowning hundreds of small settlements and multiple villages (see Fig. 2, S3B). The town of Daho is completely flooded and Ghauspur flooding has begun. The breach of the northern levee (*hereafter called the northern avulsion*) has begun. The floodwater front along the modern Indus floodplain is 80 km downstream of the Sukkur Barrage.

Day 221, Aug 9 – Floodwater rises downstream of the Sukkur Barrage where contained within the stop-banks of the modern Indus floodplain.

Day 222, Aug 10 – Flooding occurs over the levee northwest of Sukkur in three locations and generating three arms (see Figure S4A, B) that spread eastward 15 km; Ghauspur, Kharampur, Toj, Thul are submerged. The flood wave along the modern Indus floodplain has reached Dadu, 181 km downstream of the Sukkur Barrage.

Day 223, Aug 11 – The three main turbid cores of the northern avulsion have advanced 32 km (see Figure S4A); each core has a forward flood wave rim of turbid

water backed by less turbid water (Figure S4B). The modern Indus floodplain wave advances 43 km.

Day 224, Aug 12 – The northern avulsion is 50 km in length from Ghasupur to Dena; Khandh Kot, Thul, Irazi Saidki are partially flooded (Fig. 1, S5). The modern Indus flood wave has advanced 12 km.

Day 225, Aug 13 – The northern avulsion is now 75 km in length, ~11 km in width, 1-3 m in depth; two of its main arms have merged, 2 new smaller arms have appeared; the modern Indus floodplain wave has advanced 12 km to reach Sann.

Day 228, Aug 16 – The northern avulsion advances 25 km; Sohbatpur city and Dera Allah Yar cities are flooded. The modern Indus flood wave advances 45 km to reach Matiara.

Day 229, Aug 17 – The modern Indus flood wave advances 20 km to reach the Kotri barrage in Sindh; the northern avulsion advances 20 km to reach the main Northwestern Canal.

Day 230, Aug 18 – The northern avulsion advances 28 km reaching Ghari Khairo a distance of 120 km from the original breach, covering a total area of 2,670 km² and inundating ~530 villages and 13 towns and cities; the two minor arms have merged into one (Figure S3B).

Day 231, Aug 19 – The modern Indus flood wave continues to rise behind the Kotri barrage, contained within the stop banks; the northern avulsion advances 30 km.

Day 232, Aug 20 - The northern avulsion advances 15 km and extends an arm to the western foothills constrained by the Kirthar Canal (a few km to the west of Jafarabad), and also advances 30 km to the south to threaten Shikarpur (Figure S4C). Two main cores of turbid water occur continuously within the northern avulsion to its breach.

Day 233, Aug 21 – The northern avulsion advances 20 km, splitting at its front, rapid inundation of Jacobabad begins with its airport flooded.

Day 234, Aug 22 – The arms of the northern avulsion flood wave completely join, isolating Jacobabad; the total length of the main arm is now 166 km.

Day 235, Aug 23 – The northern avulsion advances 20 km, drowning Bago Daro, floodwaters rise north of Shahdadkot (population of 300,000); turbid river water continues to pour into the avulsion from the Indus River breach. The modern Indus flood wave has advanced 60 km south of the Kotri barrage (Hyderabad).

Day 236, Aug 24 – The northern avulsion advances 20 km to the southeast of Shahdadkot. A highway Ghari Khairo Rd located between the town of Qubba Saida Khan and Kot Magsi is breached, drowning the town of QS Khan (Figure S4D). Shambani town is also drowned.

Day 238, Aug 26 – The modern Indus floodplain wave has advanced 130 km south from the Kotri barrage, with rising water reaching the river mouth; the town of Bannu and the city of Thatta on the eastern bank of Indus are threatened.

Day 239, Aug 27 – The northern avulsion waters advances to within 4.5 km of Shahdadkot. The M8 highway leading into the town of QS Khan is drowned. The breach of the southeastern bank of the Indus downstream of the Kotri barrage (hereafter known as the southern or **Delta Avulsion**) has begins to approach the town of Daro.

Day 241, Aug 29 – The northern avulsion reaches the town of Khaipur Nathan Shah, some 255 km along the flow path from the breach. The foothills arm has joined with the main arm (20 to 30 km wide and 1 to 3 m deep).

Day 242, Aug 30 – The delta avulsion advances 14 km, threatening the city of Sujawal.

Day 244, Sept 1 – The delta avulsion advances 45 km, flooding the town of Sujawal. The delta avulsion lessened the severity of flooding further south in Thatta District.

Day 245, Sept 2 – The delta avulsion advances and drowns the town of Abhoro Hingora (Figure S3C).

Day 250, Sept 7 – Floodwaters recede in the modern Indus floodplain north of the Sukkur barrage, less water enters the northern avulsion from the original breach. Water levels are starting to recede from around the northern cities of Jacobabad and Shikarpur. Floodwaters have reached Lake Manchar along a flow path of 354 km. The delta avulsion has split into two arms, the northern arm advancing 83 km from the breach (carrying most of the water) and the southern arm advancing 100 km from the breach, both arms have reached the intertidal flats. Day 252, Sept 9 – The floodwaters north of the Sukkur barrage and within the modern Indus floodplain have fallen sufficiently low to expose meander bars. The delta avulsion has advanced 20 km.

Day 253, Sept 10 – The only water entering the northern avulsion is from the main Indus River channel, indicating that the breach scoured to a surface below the modern Indus floodplain. The northern avulsion continues to expand southward.

Day 259, Sept 16 – Over 7,490 villages, 135 towns/cities have been affected by the flood waters, the majority of villages completely inundated or surrounded by flood waters; >5,000 km of primary or secondary roads, 400 km of railway tracks and 400 bridges have been submerged. Satellite-detected floodwaters during this event was 37,280 km² based on cumulative analysis from 28 July to 16 September 2010.

Day 260, Sept 17 – Water is pouring out of the greatly expanded Lake Manchar and returning back into the Indus River (Figure S4E).

Day 261, Sept 18 – Two large and deep channels cut by the levee breach feeding the northern avulsion are revealed with the receding floodwaters (Figure S4F).

Day 275, Oct 2 – The Indus River discharge is greatly reduced. The northern avulsion continues to dry out and the upper half of the avulsion pathway has greatly reduced water levels. Yet the southern half of the avulsion continues to be under maximum flood conditions. The delta avulsion begins to recede in size.

Day 279, Oct 6 – Floodwaters have continued to spread from Lake Manchar to the northeast, flooding an estimated 60 villages and small towns.

Day 303, Oct 30 – Drying out continues. The delta avulsion is only a series of isolated lakes each about 5 to 15 km in diameter. The northern avulsion continues to shrink. Floodwaters are not expanding anywhere.

Day 365, Dec 31 – Nearly 98% of the floodwater has dissipated, with only isolated small areas of water, 150 days after initiation of the flood.

River Discharge

NASA/JAXA's Advanced Microwave Scanning Radiometer - EOS (AMSR-E) data were used to measure the Indus River discharge from orbit. AMSR-E provided neardaily coverage with minimal interference from clouds: this is a sampling interval adequate for measuring the local arrival times, amplitudes, and durations of the Indus River flood wave. Discharge is based on changes in the surface water areal extent within a 5 km radius of a target coordinate centered over the river.

The AMSR-E discharge technique (Brakenridge et al., 2007) employs the exceptional sensitivity of certain microwave frequency/polarization configurations to the relative coverage of water and land within a pixel. The AMSR-E band at 36.5 GHz, descending orbit, horizontal-polarization real-time swath data were used. The discharge estimator is a ratio of calibration-target radiance (expressed as brightness temperature), for a local land target unaffected by the river and outside of the measurement radius, to measurement-target brightness temperature. When measurement target water area changes, the bulk pixel brightness temperature responds; other factors affecting

brightness temperature are removed by use of the ratio with pixels near to the river but not including it (Brakenridge et al, 2007, Brakenridge et al, in press). The AMSR-E daily time series at the time of the summer, 2010 flood was 8 years.

Four Indus River reach sites were used in this study:

1) Measurement site 2011-Kotri Allahrakhio, (Fig. S5a), centered at lat. 24.2464° , long 67.8041°, a river bend site, with a 5yr recurrence flood at 10,407 m³/s.

2) Measurement site 2010-Hala, (Fig. S5b), centered at lat. 25.9010° , long 68.2609°, a river bend site, with a 5yr recurrence flood at 17,919 m³/s.

3) Measurement site 2009, (Fig. S6a), centered at lat. 28.0741° , long 69.1504°, a river bend site, with a 5yr recurrence flood at 16,771 m³/s.

4) Measurement site 2008-Ghauspur, (Fig. S6b), centered at lat. 28.0741°, long 69.1504°, a river bend site, with a 5yr recurrence flood at 16,771 m^3/s .

These Indus AMSR-E discharge values were calibrated using the CCNY Water Balance Model (WBM) a spatially and temporally explicit multi-scale (local through global) hydrological modeling scheme (Cohen et al., 2011; Wollheim W. M. et al., 2008). WBM incorporates soil moisture, precipitation, potential evapotranspiration, and irrigation (from small reservoirs, shallow groundwater, deep aquifers). Flow routing is implemented using the Muskingum equation, a semi-implicit finite difference solution to the St. Venant equations. Avulsion discharge (Figure S7) is determined from combining the velocity of the avulsion front along with flood inundation mapping as projected onto the SRTM-determined digital elevation model to ascertain flow width and water depth (Figure S8).

Digital Elevation Model

Methods: The NASA, NGA (formerly NIMA) Shuttle Radar Topography Mission (SRTM) obtained interferometric synthetic aperture radar (InSAR) data during an 11-day 2001 mission to generate high-resolution digital elevation data for the Earth's landmass located between 60°N and 59°S (Farr T.G. et al., 2007). The vertical precision of SRTM data depends considerably on location, terrain characteristics and surface feature properties. An Indus floodplain Digital Elevation Model (DEM) was developed from SRTM C-band data (5.6 cm wavelength), with its vertical RMSE (root mean square error) between 1.1 to 1.6 m, typical of flat-lying areas(Schumann G. et al., 2008) and spatial resolution of 3-arc seconds. The DEM had the ocean height tidally adjusted using TOPEX/Poseidon (Farr T.G. et al., 2007). A vector shoreline database (SRTM Water Body Data) produced by NGA depicts the ocean coast, lake shorelines, and rivers, where the ocean elevation is set to 0 m, lakes of 600 m or more in length were flattened to a constant height, and rivers that exceeded 183 m in width were delineated and monotonically stepped down in height(Farr T.G. et al., 2007). Most of the Indus floodplain is without the influence of a significant vegetation canopy.

Observations: The modern Indus floodplain channel is super elevated above the general Indus floodplain (Fig. 2, Figure S8). Once a levee is breached, waters flow away from the river to rejoin the river >350 km downstream (Fig. 1, Figure S3d).

Erosion and other Impacts

Methods: A variety of parameters were measured to provide evidence of the impact of the flood, with respect to both sediment erosion and deposition. <u>River sinuosity</u> is calculated as the ratio between the channel length as measured along the center of the channel, to the valley length as measured as the down-slope distance of the midpoint between the stop-bank levees. Sinuosity changes were compared between the February 2000 SRTM survey and both the pre- and post-flood 2010 values that were derived from MODIS and verified with Landsat 5 data. <u>Lateral migration rates</u> were calculated every two kilometers by using the centerline of the 2000, and 2010 pre and post-flood analysis. Centerlines are compared using a series of perpendicular lines generated for the early date, and the distance between the centerlines was calculated. The average of these distances of lateral migration is determined between time intervals.

Observations: The Indus sinuosity as measured from Sukkur Barrage to the Indus River mouth was 1.78 in 2000, 1.81 as measured one month before the 2010 flood, and 1.71 as measured two months following the 2010 flood. Between the 2000 SRTM survey and the 2010 MODIS pre-flood survey, the mean lateral migration of the Indus was 11 m/y. During the 2010 flood, the lateral migration rate was 338.9 m in just 52 days. The average lateral migration between the 2000 survey and the post-flood survey was 463.8 or 42 m/y, a value close to the Indus historical value of 35 m/y. Therefore the river's lateral migration occurs mostly during high intensity floods like 2010 flood. Migration rates during the 2010 flood exceed 2 km in locations. Channel widening was observed by comparing the width of the riverbanks using very high resolution Geo-Eye imagery before (typically 8 to 10 months before the 2010 flood) and immediately after the 2010

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flood. In most locations the channel widened by 30-50%, but in places the channel widened in excess of 100%. Channel bank sand deposition was near continuous in many locations and occurred along more than 50% of the river length.

Avulsion: The emphasis on gradient advantages in studies of avulsion is misleading. While gradient advantages are indeed necessary for an avulsion to occur, the late Holocene avulsion history of the Mississippi River in Louisiana suggests that factors such as substrate composition and floodplain channel distributions are more important(Aslan et al., 2005; Phillips, 2008; Törnqvist and Bridge, 2006). Because the water entering a crevasse channel is derived from relatively high in the main flow, it contains lower concentrations of sediment. Consequently, the crevasse flow is under capacity and erosive at the point of breach. Deepening of the entrance increases the crevasse-channel discharge, and the concentration of suspended solids supplied, as more sediment-laden waters are tapped from the deeper flow in the main channel. The crevasse entrance is predicted to deepen until the suspended solids entering from the main channel can satisfy its sediment-carrying capacity. Whether an avulsion will occur for a particular combination of initial conditions depends upon whether there exists steady-state hydraulic and sediment-transport conditions for crevasse channel depths that are equal to or less than the main-channel depth (Slingerland and Smith, 1998).

Breach Status: The southern delta avulsion breach of the 2010 Pakistani Flood scoured to great depth (Figure S9) and has been temporarily repaired. The breach was 420 m wide. Multiple breaks downstream were observed (Figure S9), also registering significant scour. The northern avulsion breach also saw floodwaters scour down to below the modern Indus floodplain (Figure S10). The town of Ghauspur was completely flooded by the northern avulsion (Figure S10), whereas the town of Gharhi Khairo was flooded only around its periphery, drowning buildings, canals and roads (Figure S11). As the northern avulsion floodwaters progressed, many canals were severely damaged (Figure S12). Flood sedimentation occurred over a wide area (Figure S12)

Figures and Captions



Figure S1. A particularly strong rainfall period over Pakistan on July 28, 2010 with totals in mm over the 3-hour period 00:00 to 03:00. Data are TRMM-derived rainfall estimates provided by algorithm 3B-43.



Figure S2. Four Terra MODIS near-infrared images of the Indus 2010 flood. Flood water is shown as black/blue, vegetation as green, exposed rock or sediment as shades of pink or light brown. A) July 31, 2010; B) August 18, 2010; C) September 3, 2010; D) September 21, 2010. Images highlight the filling of the Indus modern floodplain and the advancement of both the Northern (Sindh) Avulsion, and Southern (Delta) Avulsion.



Figure S3. MODIS near-infrared (A, B, D, F) or visible (C, E) images of the Pakistan 2010 flood. A) Julian Day 222-aqua, B) Day 223-terra, C) Day 232-terra, D) Day 236-aqua, E) Day 260-terra, F) Day 270-aqua. Images detail the northern avulsion: 1-3: three initial arms, 4: forward flooding zones downstream of main flood wave, 5: levee overtopping between Kharampur and Ghauspur, 6: main levee breach between Ghauspur and Daho, 7: overtopping between Daho and Haibat Khan Golo, 8: front of flood rimmed with turbid water, 9: turbidity clears along the 140+ km path with sedimentation within the first 75km, 10: north arm of Northern Avulsion constrained by the Northwestern Canal, 11: breaching of Ghari Khairo Rd, 12: water rises along the southern border of the Northern Avulsion, 13: turbid Indus water flows around Lake Manchar and back into the Indus, 14: an arm of the Indus River connected directly to the Northern Avulsion breach, 15: channels scoured by the avulsion are revealed as the floodwaters recede.



Figure S4. ASTER image data from June 28, 2010 of the breach area of the Northern Avulsion. A) ASTER blue wavelength is able to penetrate the flooded farmland below the water level to reveal active transport pathways including areas of erosion and deposition. B) ASTER near infrared shows only the water surface with mostly canal levees above the water line.



a.



Figure S5. a: River measurement site 2011, Kotri Allahrakhio, (Indus delta, nearest the

river mouth; see Fig. 1) based on AMSR-E satellite-estimated discharge as calibrated by the WBM runoff model (Cohen et al., 2012; Cohen et al., 2011). The upper plot is for discharge in m^3/s for the year 2009 and 2010, and a portion of 2011. The lower plot is for discharge from August 2002 to early 2011. b: Flood Observatory Station 2010, Hala, (upstream of 2011; see Fig. 1). The upper plot is for discharge in m^3/s for the year 2009 and 2010, and a portion of 2011. The lower plot is for discharge from August 2002 to early 2011. The remote sensing time series demonstrates that the 2010 flood is the largest flood at these sites during this period, in peak magnitude, duration, and discharge volume.



a.



b.

Figure S6a. Measurement site 2008, Ghauspur, upstream of site 2010 (see Fig. 1). The upper plot is for discharge in m³/s for the year 2009 and 2010, and a portion of 2011. The lower plot is for discharge from August 2002 to early 2011. S6b. Measurement site 2009, Chacharan, (upstream of the Northern Avulsion and site 2008, see Fig. 1). Peak discharge and floodplain inundation at 2009, furthest upstream of the four sites, occurred on August 24.



Figure S7. Avulsion discharge determined from combining the velocity of the avulsion front (lower graph, and see Fig 1) along with flood inundation mapping (Fig. 1) onto the SRTM-determined digital elevation model to ascertain flow width and water depth (Figure S8).



Figure S8. SRTM-derived digital elevation model showing the modern Indus River channel and its floodplain stop-banks. The generalized topographic contours (every 10m) are overlain on the DEM. Colors change every 1 m and repeat every 10 m until 100 m, then black. The modern Indus floodplain is super-elevated above surrounding floodplain.



Figure S9. GeoEye image close up of the southern Delta Avulsion breach of the 2010 Pakistani Flood showing scour zone and temporary levee repair. The breach is 420 m wide. Also shown are the breaks through a secondary road that has also been temporarily repaired.



Figure S10. Before, during and after images (ASTER – A, B; Landsat 5 - C) of the Northern Avulsion breach showing that the flood waters scoured down to below the modern Indus floodplain. The town of Ghauspur is completely flooded in B).



Figure S11: GeoEye image of the town of Gharhi Khairo with peripheral drowning of buildings, canals and roads by the Northern Avulsion.



Figure S12: GeoEye images of Northern Avulsion floodwaters of the 2010 Pakistan Flood. A) & B) Note the many breaks of the floodwaters across the otherwise subaerial canals. C) Crevasse splay deposit from floodwaters that broke through a canal levee.

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