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RESEARCH ARTICLE

Widespread infilling of tidal channels and navigable waterways in the human-modified tidal deltaplain of southwest Bangladesh

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Since the 1960s, ~5000 km^2 of tidal deltaplain in southwest Bangladesh has been embanked and converted to densely inhabited, agricultural islands (i.e., polders). This landscape is juxtaposed to the adjacent Sundarbans, a pristine mangrove forest, both well connected by a dense network of tidal channels that effectively convey water and sediment throughout the region. The extensive embanking in poldered areas, however, has greatly reduced the tidal prism (i.e., volume of water) transported through local channels. We reveal that >600 km of these major waterways have infilled in recent decades, converting to land through enhanced sedimentation and the direct blocking of waterways by embankments and sluice gates. Nearly all of the observed closures (~98%) have occurred along the embanked polder systems, with no comparable changes occurring in channels of the Sundarbans (<2% change). We attribute most of the channel infilling to the local reduction of tidal prism in poldered areas and the associated decline in current velocities. The infilled channels account for ~90 km^2 of new land in the last 40–50 years, the rate of which, ~2 km^2/yr, offsets the 4 km^2/yr that is eroded at the coast, and is equivalent to ~20% of the new land produced naturally at the Ganges-Brahmaputra tidal rivermouth. Most of this new land, called 'khas' in Bengali, has been reclaimed for agriculture or aquaculture, contributing to the local economy. However, benefits are tempered by the loss of navigable waterways for commerce, transportation, and fishing, as well as the forced rerouting of tidal waters and sediments necessary to sustain this low-lying landscape against rising sea level. A more sustainable delta will require detailed knowledge of the consequences of these hydrodynamic changes to support more scientifically-grounded management of water, sediment, and tidal energy distribution.

Keywords: deltas; tidal channel siltation; anthropogenic modification; land reclamation

1. Introduction

It is becoming increasingly apparent that direct human manipulations in naturally dynamic deltas and their watersheds have to date had a substantially greater impact than climate change or global sea-level rise (Day et al., 2000; Ericson et al., 2005; Syvitski et al., 2009; Giosan et al., 2014; Higgins et al., this issue). Among these human modifications, fluid extraction (e.g., water, hydrocarbons) accelerate natural subsidence rates and river channel embankments lead to elevation deficits from sediment starvation, which put millions at risk worldwide to flooding from annual river pulses and high magnitude low frequency events such as storm surges (Syvitski et al., 2009; Auerbach et al., 2015). In the vulnerable, densely-populated Ganges Brahmaputra tidal deltaplain (southwest Bangladesh, population >20 million in the region), coastal planners and engineers have known for the greater part of a century that morphologic changes would result from embanking vast areas of intertidal land (major building persisted 1961–1978; Addams Williams, 1919; Mahalanobis, 1927; Mukerjee, 1938; Alam, 1996). Sediment starvation and channel siltation were expected in response to this engineering plan (Addams Williams, 1919), however research on the impacts of widespread embanking in this portion of the delta remains sparse and is only beginning to be critically evaluated (Pethick and Orford, 2013; Brammer, 2014; Auerbach et al, 2015). Here, we quantify some of the profound morphologic changes that have occurred to the intertidal platform and channel network since the widespread construction

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of embankments began in the tidal deltaplain circa 1960s. Using a compilation of historical imagery and observational data, we map the distribution and area of infilled tidal channels and calculate the mass of sediment trapped within them. We subsequently discuss the effects of altered sediment distribution patterns and implications for the communities that live on this altered landscape and rely on open waterways for transportation and commerce.

2. Study area

Under natural conditions, the tidal deltaplain of southwest Bangladesh consists of a dense network of interconnected channels and mangrove islands inhabited by ecologically important and endangered fauna, including the Royal Bengal tiger and Ganges and Irrawaddy river dolphins (Smith et al., 2009; Ortolano et al, 2016). In this landscape, major tidal channels (1–2 km wide) convey semi-diurnal tides >120 km inland of the coast, delivering sediment-laden water to secondary channels and the primary creeks that normally flood and drain the mangrove-vegetated intertidal platforms (**Figure 1**; Allison and Kepple, 2001; Rogers et al., 2013). The tidal range varies from ~2 m at the coast (Hiron Point), amplifies inland to ~3.5 m at Mongla and 3 m at Khulna, before decreasing further inland (**Figure 1**; EGIS, 2000; BIWTA, 2010). Waning freshwater discharge down Ganges river distributaries (e.g., Gorai, Kobadak) results in saline water intrusion

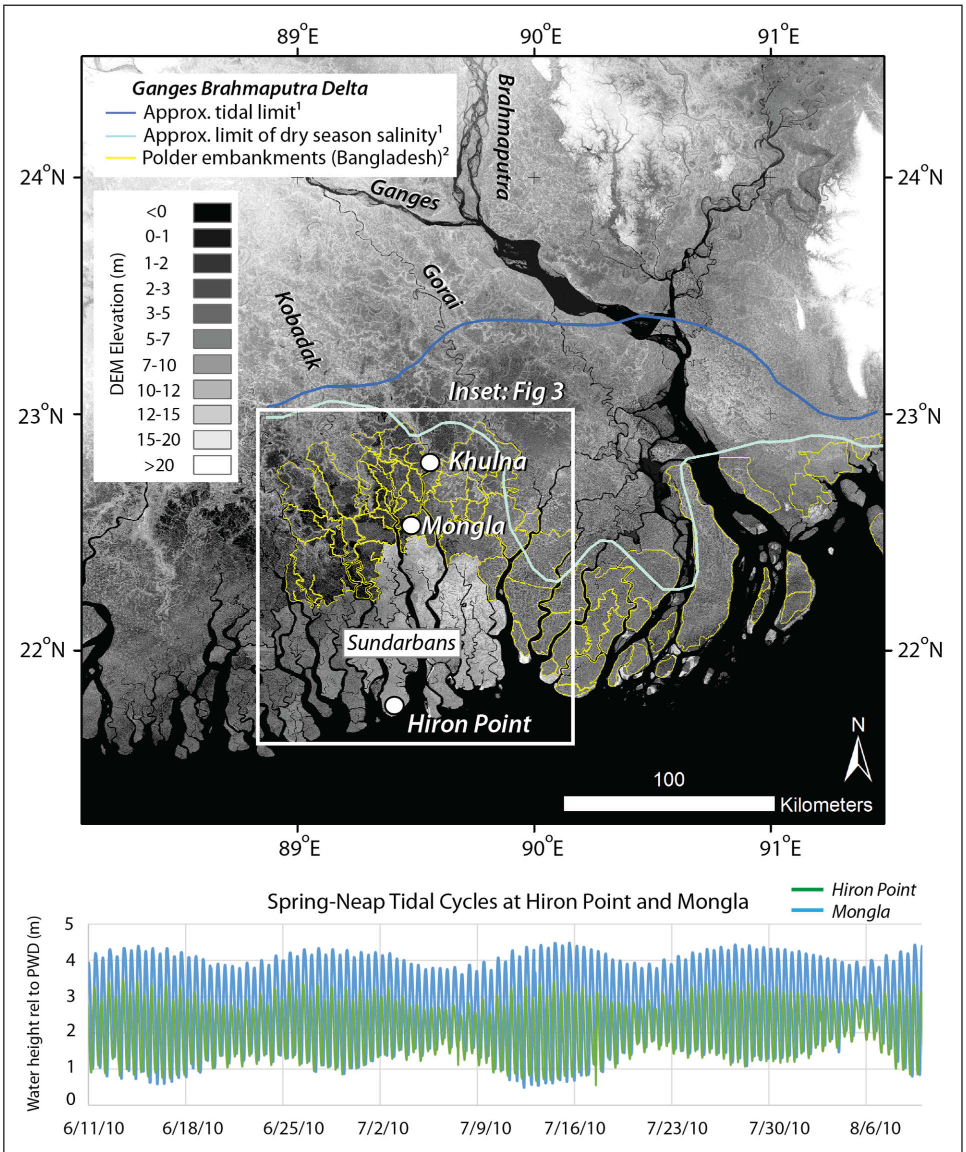

Figure 1: Ganges Brahmaputra delta: elevation, tidal limit, and salinity incursion. *Top:* Digital elevation model of the tidal deltaplain of the Ganges Brahmaputra delta, southwest Bangladesh, including locations of the tidal limit, salinity incursion during the dry season, the Sundarbans mangrove forest preserve, and inhabited poldered islands. Elevations from 1 arc-second SRTM 2000 measurements downloaded from Earth Explorer. Note elevation for the Sundarbans is exaggerated due to tree canopy cover; it exists at ~MHW, ~1.5 m above most poldered landscapes (Auerbach et al., 2015). *Bottom:* Spring-neap tidal cycles at Hiron Point and Mongla, obtained from hourly data provided by the Bangladesh Inland Water Transportation Authority (BIWTA, 2010). Note the tidal amplification inland at Mongla. ([1]FAO, 1985; [2]CERP, 2005). DOI: https://doi.org/10.1525/elementa.263.f1

during the dry season that extends more than 100 km inland (**Figure 1**). This has been exacerbated in recent decades from sediment choking of the main Gorai offtake channel at the Ganges confluence (Winterwerp and Giardino, 2012).

This region of intersecting fluvial distributaries and tidal channels, about 60–130 km inland of the coast, is relatively low, poorly drained, and among the areas most susceptible to storm surges, sea-level rise and waterlogging (Wilson and Goodbred, 2015). Beginning in the late 1960s and continuing to the early 1980s, ~5000 km^2 of this low-lying tidal deltaplain was embanked and converted to densely inhabited, agricultural islands (i.e., polders; **Figure 1**). This anthropogenic landscape lies adjacent to the Sundarbans, ~5000 km^2 of pristine mangrove forest (**Figure 1**). Within the human-altered landscape, the construction of major embankments for the polder systems immediately cut off >1000 km of primary tidal creeks that once connected the islands to adjacent tidal channels, precluding the natural exchange of water and sediment that defines the delta plain (Pethick and Orford, 2013). Without the regular delivery of sediment to the land surface from tidal overbank flooding over the last 50 years, significant loss in elevation (1–1.5 m) relative to mean high-tide levels has occurred, culminating in enhanced flood risk in the event of embankment failure (Auerbach et al., 2015). Recent research also indicates that the tidal range has increased inland due to polder construction, with high water levels within the polder zone increasing as much as 1.7 cm/yr in recent decades (Pethick and Orford, 2013). Finally, prevalent siltation of tidal channels has been reported in the literature (Alam, 1996; Barkat et al., 2000), but its magnitude, distribution, and consequences have remained poorly resolved. This study focuses on these issues to help elucidate the extent and location of infilled channels, and to understand the contribution of infilling to regional and delta-wide sediment budgets.

3. Methods

Evaluation of the tidal channel network and historical changes was performed using GIS analysis of Landsat and recent Google Earth imagery within six 1000 km^2 study areas of the tidal deltaplain (**Figure 3**; Supplemental Material). Three grids were selected within poldered regions and three within the Sundarbans mangrove forest as a control. All six grids contain a similar ratio of ~30:70 for original water to land area. In GIS, shapefiles of the tidal creeks were created with total length and average width calculated for each year in each grid. Bank lines were identified as the border between vegetated and unvegetated surfaces in the Landsat imagery, and only images from the same tidal level were analyzed (tide gauge data obtained from Bangladesh Inland Water Transportation Authority, BIWTA, 2010; **Figure 1**). Polder embankment lines were obtained from the Coastal Embankment Rehabilitation Project (CERP), Bangladesh (2005). Tidal creek and polder embankment shapefiles for years analyzed can be readily accessed and downloaded from the Supplemental Material.

The earliest historical Landsat MSS imagery (1972–1973) was used to analyze the tidal deltaplain and channel network in a relatively pristine state at the beginning stages of the major embankment practices, while Landsat TM and ETM+ imagery from subsequent decades was used to analyze the anthropogenically-modified state (**Figure 2**; Supplemental Material). In poldered regions, embankment lines were used to analyze which primary and secondary tidal channels had conveyed regular tidal exchange prior to embanking (water exchange thereafter controlled by sluice gates). On-the-ground field validation of imagery and mapping was performed in October 2013, May 2014, and March 2015 to confirm closed channel locations, channel widths, and land use.

Changes in tidal prism and vertical sediment accretion in the channels were quantified using a combination of field measurements including channel geometry, bathymetry and coring (see Supplemental Material for details).

4. Results and Discussion

4.1. Modification to the tidal channel network and quantified land gain

Historical satellite imagery from the Sundarbans mangrove forest (the natural tidal deltaplain) shows that the tidal-channel network in the region has remained relatively stable since the 1970s with <2% net change in the length of waterways and relatively small changes in channel widths (**Table 1**; Figures S1, S2, and Table S1 in Supplemental Material). Most bank line changes in the Sundarbans over this time have taken place along the exposed coast, with lateral migration (i.e., limited net shoreline erosion) occurring within the tidal channels themselves (Allison, 1998; Sarwar and Woodroffe, 2013; Small et al., *in prep*). The Sundarbans tidal deltaplain thus appears to have, on average, remained in a relatively steady state in terms of tidal exchange and the import of sediment to offset relative sea-level rise (Rogers et al., 2013; Brammer, 2014, Giri et al., 2007). Juxtaposed to this, however, the poldered landscape that was once intertidal like the Sundarbans has exhibited profound geomorphic adjustment over the same time period.

In the poldered landscape, we quantify the closure of >1000 km of primary creeks due to direct blocking by embankments and sluice gates (similar to that documented by Pethick and Orford, 2013; **Table 1**). Further, polder construction greatly reduced the local tidal prism transported by the remaining channels (>1000 × 10^6 m^3; Pethick and Orford, 2013), reducing local current velocities and favoring enhanced sediment deposition. It is for these 'conduit' tidal channels located *outside* of the polders that we document extensive infilling, with >400 km of major waterways closing to <50% of their original width (**Figures 2** and **3**; **Table 1**; see also Figures S1, S2, and Table S1 in Supplemental Material). Many of these narrowed channels have become restricted by large sluice gates emplaced between polder islands, while others have simply become "dead-end" channels due to polder construction (**Figure 2**; see also Supplemental Material). Overall, most infilling has taken place along channels that have lost one or more connections with the

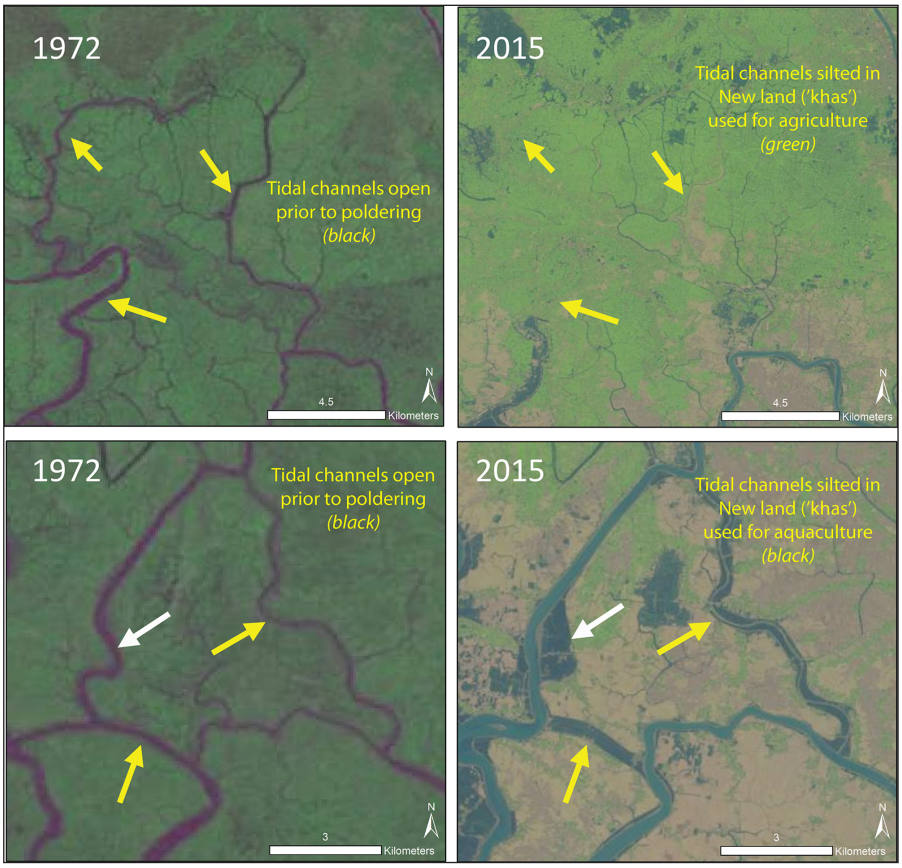

Figure 2: Tidal channel morphologic changes in recent decades. Conduit tidal channels outside of polder embankments (highlighted by yellow arrows) exhibit significant infilling across the region between 1972 and 2015. Many of these channels have simply become "dead-end" channels due to polder construction, while others have tidal restriction due to large sluice gates emplaced between polder islands. Many of these channels are reclaimed for rice agriculture or shrimp aquaculture, as shown in figures at right, and locally called 'khas land'. A reorganization of tidal water transport can also be seen in the images on the bottom right with channel straightening and widening of remaining unrestricted channels. DOI: https://doi.org/10.1525/elementa.263.f2

Table 1: Summary of results from GIS analysis of historical Landsat imagery, 1973–2013 (see Figure 1 for locations, Table S1 for detailed measurements within each study grid). DOI: https://doi.org/10.1525/elementa.263.t1

	Poldered Areas			**Natural Areas**		
Year	1973*	2003	2013	1973*	2003	2013
Length of tidal channels outside of polders (km)	1891	783	782	1964	1987	1981
Length of tidal channels obstructed by polders [1° creeks] (km)	0	1108	1108	0	0	0
Length of tidal channels outside of polders with >50% obstruction [khas land] (km)	0	355	420	0	0	0
% change in drainage network			**−59%**			**1%**
% of conduit channels converted to khas land		**45%**	**54%**			**0%**

tidal network, reducing their local discharge and favoring enhanced sediment deposition (**Figure 2**).

The cumulative effect of these channel responses result in a 90% decrease in the mean width (256 ± 91 m to 25 ± 10 m) of affected channels and a 60% decrease in their average depth (5.0 ± 1.0 m to 2 ± 1 m, **Figures 1** and **3**; see Figure S3 in Supplemental Material; also Rahman et al., 2013). In total, the aggregate loss of tidal waterways accounts for a 60% decrease in total channel length across the ~3000 km^2 of poldered area studied in the three grids (**Table 1**) – this corresponds to a loss of nearly two thirds of the region's navigable waterways over the past 40 years. It is significant to note that nearly all of the observed closures (~98%) have occurred along

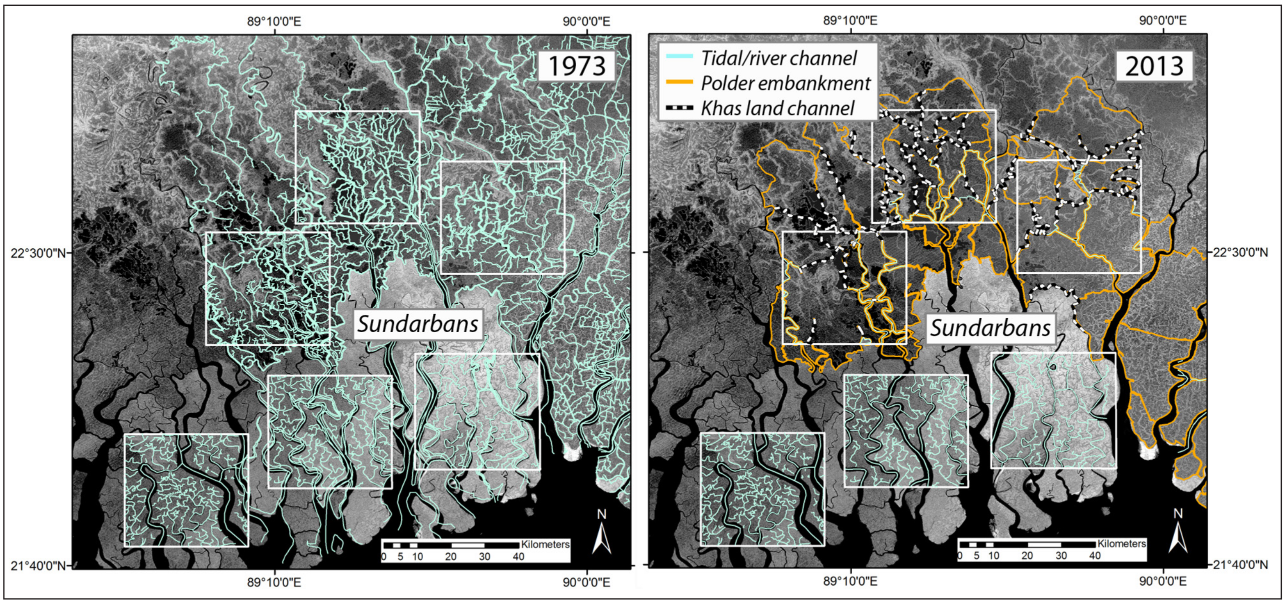

Figure 3: Tidal channel network under natural (pre-polder) and anthropogenic (post-polder) conditions. Conduit channels that have infilled greater than 50% (i.e., 'Khas' land) delineated from historical Landsat imagery in the 6 study areas in southwest region of Bangladesh, 1973–2013. The 3 white boxes on top are located within poldered areas, while the 3 on bottom are within the Sundarbans mangrove forest and serve as control sites. See also Supplemental Figure S1 for unedited and traced imagery for each study area. DOI: https://doi.org/10.1525/elementa.263.f3

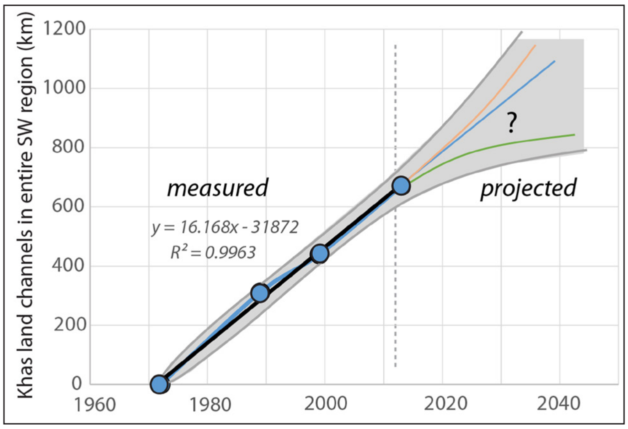

Figure 4: Infilling channels and formation of 'khas land', 1973–2013. Rate of infilling channels (and formation of 'khas land') was measured from shapefiles delineated from historical imagery. If the rate of khas land channel formation remains the same in coming decades, as much as 1000 km of conduit channels outside of the polders could silt in by 2030. DOI: https://doi.org/10.1525/elementa.263.f4

the embanked polder systems, with no comparable changes occurring in channels of the Sundarbans (<2% change) (**Figure 1**; **Table 1**). We therefore attribute most of the channel infilling to the local reduction of tidal prism in poldered areas (Pethick and Orford, 2013) and the associated decline in current velocities.

A temporal analysis of satellite imagery indicates that the infilling of channels in the poldered region has progressed at a linear rate of ~16 km/yr of channel loss over the past 40 years (R^2 of 0.99; **Figure 4**), culminating in the closure of >600 km in the entire tidal deltaplain by 2013, including 440 km within the focus areas and another 200 km measured outside our study grids (**Figures 3** and **4**). The infilled waterbodies observed here are transformed from large, navigable tidal channels that provide public fishing grounds and aquatic habitat, to well-defined land plots that are, not surprisingly, rapidly reclaimed and typically cultivated for either agriculture (i.e., rice) or aquaculture (i.e., shrimp; **Figure 2**, S4) (Barkat et al., 2000). In Bangladesh, new lands constructed within the river delta, such as these infilled channels, are locally known as "khas land", or government-owned property, and are intended for distribution to the economically poor and landless people of the nation (Barkat et al., 2000; Feldman & Geisler, 2011). From these analyses, we calculate that channel siltation and conversion of open-water tidal channel to khas land equates to a substantial land gain of >90 km^2. This average rate of +2 km^2/yr of land development is equivalent to ~15% of that produced naturally through delta progradation at the main Ganges-Brahmaputra-Meghna rivermouth (average net gain +12 km^2/yr from Allison, 1998; Sokolewicz et al., 2008; Brammer, 2014; **Figure 5**). The net gain of these khas lands also significantly offsets reported land loss of –4 km^2/yr at the coast adjacent to the poldered region (**Figure 5**; Giri et al., 2007; Rahman et al., 2011; Shearman et al., 2013; Brammer, 2014). If land gain from channel siltation in poldered areas of southwest Bangladesh are factored in, on average the Ganges-Brahmaputra tidal deltaplain, including active river mouth, has a net land gain of +10 km^2 annually (**Figure 5**).

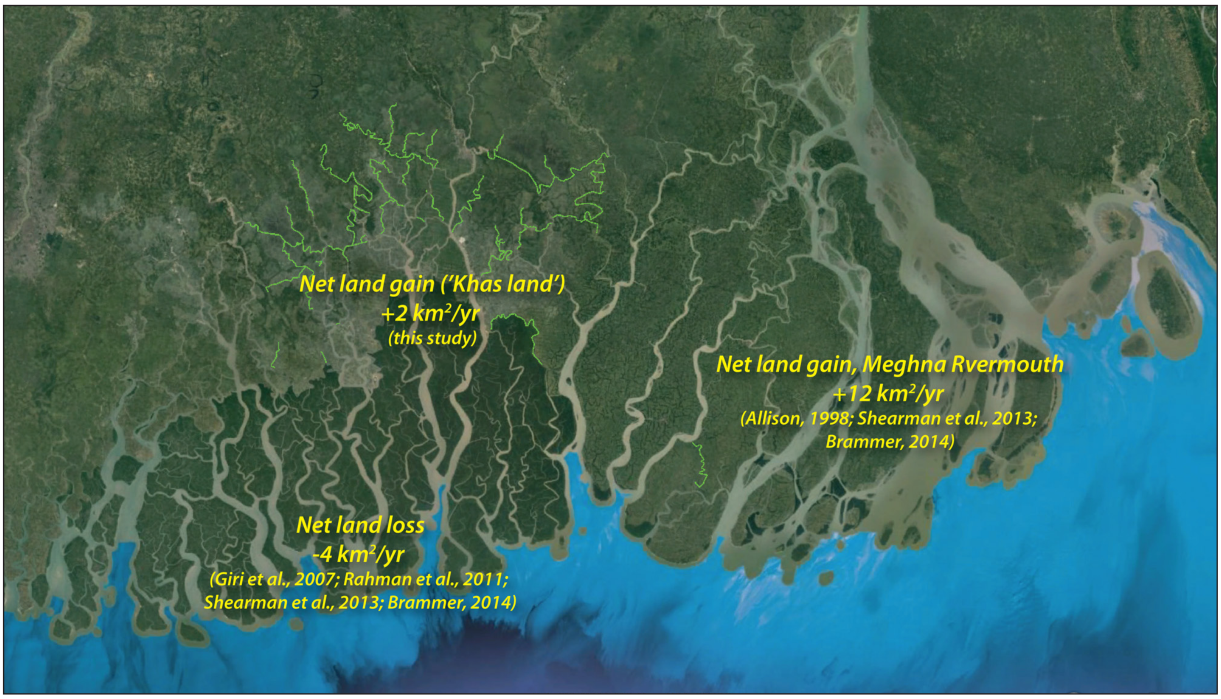

Figure 5: Net land gain and loss measured in the Ganges-Brahmaputra tidal deltaplain. If land gain from channel siltation in poldered areas of southwest Bangladesh are factored in, on average the Ganges-Brahmaputra tidal deltaplain, including active river mouth, has a net land gain of +10 km^2 annually. DOI: https://doi.org/10.1525/elementa.263.f5

4.2. Impacts to tidal prism and sediment depocenters

In the tidal deltaplain, bi-directional flow with velocities exceeding 3–4 m/s during spring tides sustain high suspended sediment concentrations and transport large volumes of sediment from the inner shelf across the tidal delta plain, up to 120 km landward (Barua et al., 1994). This long-distance propagation of the tides and the region's large intertidal areas lead to a well-developed flood-tide asymmetry that favors net sediment import from the inner-shelf sediment plume. These sediments typically accumulate where velocities diminish at the end of the transport pathway along the upstream reaches of the tidal channels or on the intertidal mangrove platform and small primary creeks (Barua; 1990; Rogers et al, 2013). Measured sediment accumulation on the Sundarbans platform indicate up to 96 × 10^6 tons of sediment per year (10% of the total annual sediment load of the Ganges-Brahmaputra river system) is trapped there during tidal inundation (Rogers et al., 2013). However, estimates of sediment sequestered in the Sundarbans tidal channels and those in the poldered landscape further inland are poorly resolved, with the latter being a focus of this paper.

Due to embankment construction, the total decrease of the tidal prism within three poldered regions of southwest Bangladesh (~3500 km^2; **Figure 3**) is ~1.4 × 10^9 m^3, expanding the estimate from previous authors for a smaller catchment area (1 × 10^9 m^3; Pethick and Orford, 2013). We calculate that two-thirds of this is due to the direct loss of intertidal landscape through embanking (700 × 10^6 m^3 of water that originally flooded intertidal platforms plus 255 × 10^6 m^3 of water that was accommodated in primary creeks), and an additional one third is from indirect infilled channel closures outside of polders (i.e., khas land; 462 × 10^6 m^3 of water once fluxed through these larger conduit channels; **Table 2**; see also Table S2). Normalized to the average 6.2 hours of a single tidal limb, the decrease of ~1.4 × 10^9 m^3 of tidal waters equates to a reduction in the regional tidal discharge of ~60,000 m^3/s per flood or ebb tide (e.g., 1.4 × 10^9 m^3/22,320 s). This loss of twice-daily water exchange is *nearly double* the ~35,500 m^3/s mean annual discharge of the entire Ganges-Brahmaputra river (Jian et al., 2009; Milliman and Farnsworth, 2013), attesting to the magnitude of hydrodynamic alterations that have led to the infilling of >600 km of major tidal waterways.

Cores collected from these infilled channels reveal a fining upward sequence of homogenous very-fine sand at the base, indicative of the current-scoured channel bed prior to poldering, grading into tidally laminated muds and fine sands capped by silty clays that together reflect diminished current velocities and infilling of the tidal channel (**Figure 6**; S4). The average fill thickness (i.e., depth to sand) is ~5 m, which has infilled over a 16 to 26-year period based on historical imagery (**Figure 4**; S4), yielding average vertical accretion rates of 19–31 cm/yr. Optically Stimulated Luminescence (OSL) dates from the base of several tidal channel fills help refine these vertical accretion rates to 12–18 cm/yr (samples 009 and 010 from Chamberlain et al., 2017). Historical observations report similar sedimentation rates for infilling channels in the Indian portion of the tidal deltaplain (~15 cm/yr;

Table 2: Calculated volumes of water removed from tidal prism in study area due to polderization, and the annual mass infill of sediment contained in 'khas-land' channels in the study area (Table S2 for details). DOI: https://doi.org/10.1525/elementa.263.t2

Description	Value
Volume of water that originally flooded intertidal platforms	700×10^6 m^3
Volume of water accommodated in primary creeks	255×10^6 m^3
Volume of water accommodated in conduit channels	462×10^6 m^3
Total volume of water removed from tidal prism due to poldering	**1,420 × 10^6 m^3**
Fraction due to khas land infilling of conduit tidal channels	32.6%
Fraction due to obstruction of primary creeks by embankments	18.0%
Fraction due to obstruction of intertidal platform by embankments	49.4%
Volume of sediment contained in khas-land channel fill	462×10^6 m^3
Mass of sediment contained in khas-land channel fill	615×10^9 kg
Annual mass of sediment infilling khas-land channels	12.3×10^9 kg

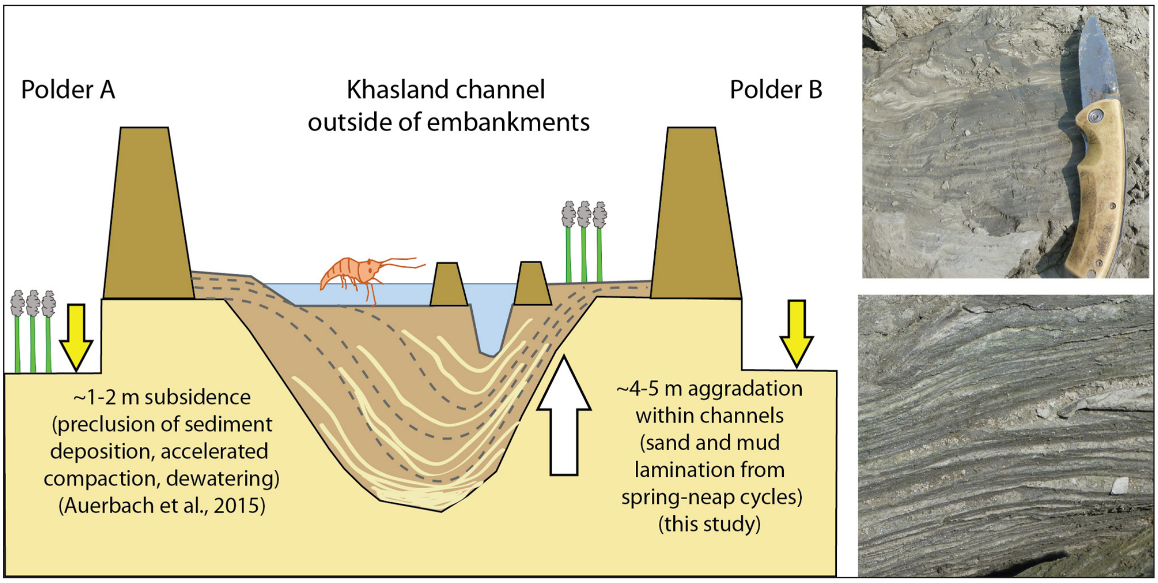

Figure 6: Channel siltation results in land reclamation (formation of 'khas land') but increased waterlogging within polders. While poldered regions exist at an elevation deficit due to sediment preclusion and accelerated compaction (Auerbach et al., 2015), aggradation within channels by interlaminated sand and mud (right) occurs due to reductions in tidal prism and current velocities. The combination of these geomorphic responses has led to many channel beds becoming shallower than polder elevations, which exacerbates waterlogging in polders. DOI: https://doi.org/10.1525/elementa.263.f6

Addams Williams, 1919). These rates are high but compare well with the average tidal sedimentation that occurred in a nearby polder after its embankments breached and remained unrepaired and subject to near-daily tidal inundation for 2+ years (18 cm/yr; Auerbach et al., 2015). It is important to note, however, these rates are several times greater than the typical 1–4 cm/yr of accretion observed on the Sundarbans mangrove platform (Allison and Kepple, 2001; Rogers et al., 2013), which can be attributed to greater accommodation space, continuous inundation, and deeper water column from which to draw sediment (Hale et al., 2017).

From the size and length of infilled channels, we calculate the volume of silty muds infilling them to be 462×10^6 m^3, which equates to 615×10^9 kg of sediment using a typical bulk density of 1330 kg/m^3 (**Table 2** and S2). Averaged over the ~50 years since the start of major polder construction (1960s to present), these deposits account for an annual deposition of 12.3×10^6 metric tons of sediment to the infilling channels. This is equivalent to ~15% of the total sediment mass annually deposited in the adjacent Sundarbans (Rogers et al., 2013) and thus represents a significant portion of the regional sediment budget for the tidal deltaplain.

4.3. Sustaining the Ganges-Brahmaputra tidal deltaplain: Land use changes and social/environmental impact

In southwest Bangladesh, tidal channels are the primary arteries for transportation of goods and people (including rice, shrimp, fuel, food, textiles, etc.), as relatively few roads and bridges span the embanked polder islands. Thus, the siltation and closure of >600 km of major conduit channels reported here may have significant impacts on regional commercial and human transportation (Alam, 1996: Rahman et al., 2013), and even stability of local cetacean populations (e.g., Smith et al., 2009). One example of the compound effects of the channel closures comes from the Mongla-Ghasiakhali tidal channel (MGC; **Figure 7**), where infilling of this east-to-west navigation route since the 1980s forced ship traffic to be rerouted through protected channels of the Sundarbans National Forest, a UNESCO World Heritage Site (Mahmud and Sharafat, 2015, 2016). This forced rerouting was a contributing factor to several recent shipping accidents, including a 350-tonne oil spill in the Sundarbans on December 9, 2014 (**Figure 7**; The Daily Star, 2014, 2015). After the accident, the Bangladesh government committed to reopening the MGC transportation route and dredged the channel in 2015, cutting off some khas land areas (**Figure 7**; The Daily Star, 2016). Further, local engineers have cautioned that polder-altered hydrodynamics will require persistent dredging operations to keep this navigation route open, requiring millions of dollars annually (Rahman et al., 2013; Haque, 2014). Despite re-opening the MGC route, much shipping continues to navigate through the Sundarbans, and several accidents leading to potential environmental disaster have been reported over the past 3 years (January 2017: *MV Aichgati*, 1000 tons of coal; March 2016: *MV Jabale Nur* 1,235 tons of coal; October 2015: *MV Ziaraj* 510 tons of coal; The Daily Star, 2016, 2017; Mahmud and Sharafat, 2015, 2016). Many local experts report the potential ecological impacts of these environmental disasters (e.g., pollution, eutrophication, fish kills, etc.), and infilled channels and forced re-routing of ship navigation remains of great concern (The Daily Star, 2016, 2017).

If the observed rate of channel closures (16 km/yr) persists through coming decades, as much as 1000 km of conduit channels outside of the polders could silt in

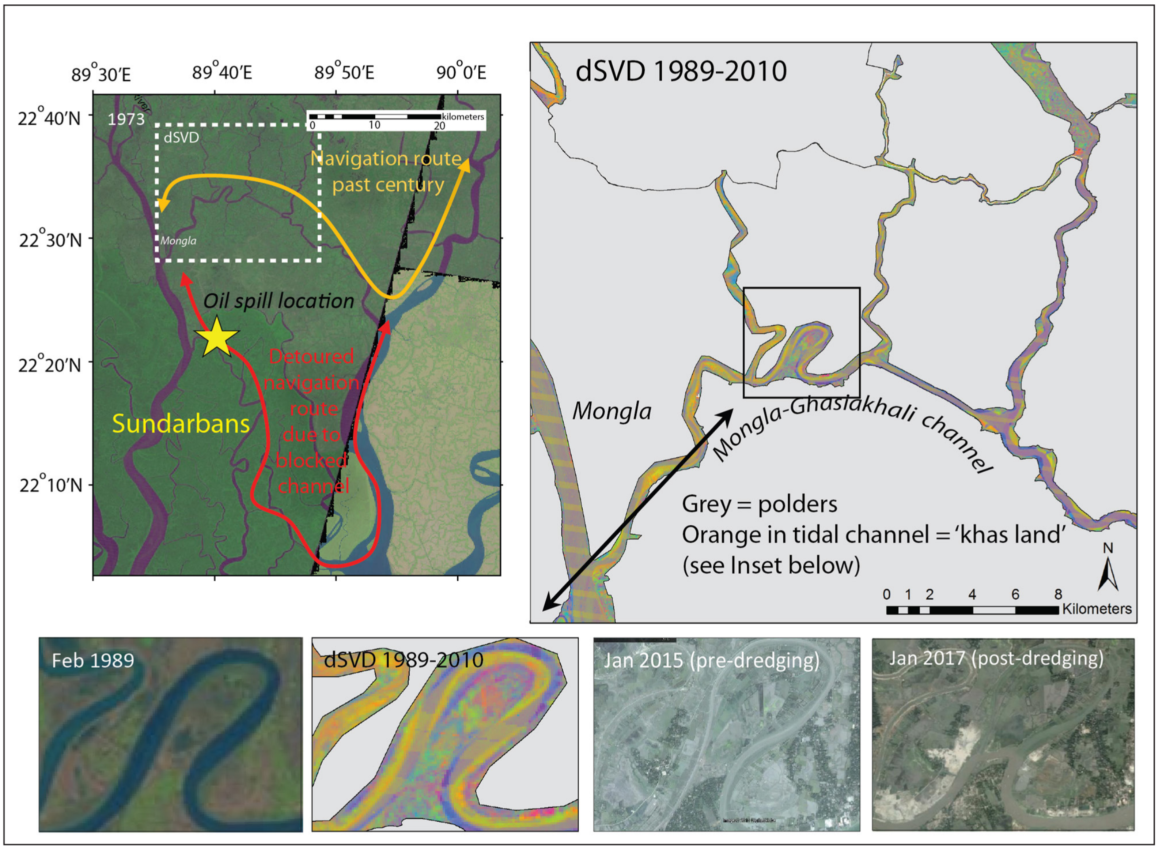

Figure 7: Channel siltation along the Mongla-Ghashiakhali navigation route between 1989 and 2016. Remote sensing images and dSVD analysis from Landsat and Google Earth imagery reveals rerouting of ship traffic into the Sundarbans mangrove forest resulted as channel siltation along the Mongla-Ghashiakhali navigation route progressed *(top left and bottom)*. dSVD conversion of measured radiance to reflectance and estimation of spectral endmember fractions allows each Landsat image pixel to be represented as areal fractions of sediment substrate (S), vegetation (V), and dark fractions (D). Differencing coregistered SVD fraction images collected at different times allows land cover changes to be represented as dSVD maps showing absolute increases and decreases in subpixel area of substrate, vegetation and water (or shadow; *top right*). See Supplemental Material for details. DOI: https://doi.org/10.1525/elementa.263.f7

by 2030 (**Figure 4**), which is a factor that needs to be considered by coastal managers and water transportation authorities. However, it is plausible that this rate will decrease as the system reaches a new equilibrium, particularly as water and sediment fluxes continue to decline due to both natural and anthropogenic factors (Winterwerp and Giardino, 2012; Higgins et al., this edition). These results highlight the necessity for further observational and modeling studies to accurately describe changes to the tidal channel network in southwest Bangladesh and predict impacts to local livelihoods and ecology.

Another effect of channel closures has been the loss of annual sedimentation previously supplied by the tides, which had sustained the elevation of the local deltaplain relative to rising sea levels (Payo et al., 2016). These tidal conduits for sediment delivery hold the key for potential restoration of the many poldered islands that lie at a significant elevation deficit due to sediment starvation and shallow compaction from embankment construction and land use practices (**Figure 6**; Auerbach et al., 2015). From a management perspective, the low elevation of many sediment-starved polders requires new sediment input to ameliorate this offset, but the infilling of adjacent tidal channels precludes active sediment delivery. Furthermore, the infilled channels also impede the drainage of local floodwaters during the wet season or cylone events as channel bed depths become shallower than polder elevations (**Figure 6**), exacerbating the depth and duration of waterlogging (Rahman, 1995; Alam, 1996; Alam et al., 2017). This has been shown to hamper agricultural production and enhance regional migration (Mallick and Vogt, 2012; Alam et al., 2017).

We show here that ~15% of the total sediment mass annually deposited in the adjacent Sundarbans is being sequestered in inland local waterbodies (**Table 2**). Dredging of these khas lands and infilled channels could restore original waterways and sediment transport paths, potentially reducing the elevation deficits that plague much of southwest Bangladesh. Such an effort, however, would be costly and require sustained and effective management through local, regional, national, and even international support. Locally, such restorations of sediment delivery and land-surface elevations have been implemented in several small areas in the tidal deltaplain through the local approach of tidal river management (TRM; Khadim et al., 2013; Paul et al., 2013). These TRM projects have had some success in both restoring local elevation and scouring partially filled-in tidal channels, but results have also been mixed due to many social and engineering challenges that could prove formidable if applied at the regional scale and TRM is only feasible where there is still sufficient tidal flow (Rahman, 1995; ADB, 2007; Kibria and Hirsch, 2011; Khadim et al., 2013; Paul et al., 2013). Nevertheless, we maintain that long-term sustainability of the delta requires the proper management of both *sediment and the tidal channels that disperse it,* in order that elevation relative to rising water levels is sustained (see also Van Staveren et al., 2017). Further research into the changes documented here and general sediment transport and hydrodynamic processes within this region of the delta are needed for developing viable land management strategies and restoring tidal waterways and their critical ecosystem services of water and sediment delivery, floodwater drainage, fisheries, and transportation (Mallick and Vogt, 2012; Hossain et al., 2016; Alam et al., 2017).

5. Conclusions

In the Ganges-Brahmaputra tidal deltaplain, we quantify direct and indirect anthropogenic alterations of the region's tidal channel network over the past several decades, including the impoundment of primary creeks during polder construction (>1000 km length) and the obstruction and infilling of major conduit channels (>600 km length), culminating in the reclamation of new land (>90 km^2) for agriculture and aquaculture purposes. While it has been acknowledged that polder construction has had an impact on local sediment transport and hydrodynamics (e.g., channel infilling and decrease in tidal prism; Alam, 1996; Pethick and Orford, 2013), the significant extent of channel closures has gone largely undocumented, as have its effects on sediment distribution patterns, land use changes, and associated impacts to the environment and transportation network. We document here that these tidal channel closures specifically impact: i) the regional tidal prism, resulting in at least a 1.4×10^9 m^3 decrease in twice-daily water exchange, ii) shifting of sediment deposition to channel infill as opposed to the previously intertidal poldered landscapes, iii) altered ship-based transport and navigation, leading to the forced rerouting of shipping traffic through the ecologically sensitive and protected regions of the Sundarbans, and iv) increased waterlogging within polders, as infilled channels preclude the delivery of sediment to polders to ameliorate elevation offsets, and channel depths become shallower than polder elevations. These findings demonstrate the importance of better understanding the cascade of effects that can result from human modification of this dynamic tidal delta plain. Although global climate change and sea-level rise remain major concerns for this region and low-lying deltas worldwide over the next century, in the short term (over the next several decades) the sustainability of deltas likely lies more directly under the control of local to regional engineering programs and management policies. Specifically our findings in the Ganges Brahmaputra delta give an example of the magnitude of historic human impacts, and where further attention and focused research efforts are needed.

Data Accessibility Statement

Datasets associated with this submission are provided in Supplemental Material. Any associated data not included in Supplemental will be archived with corresponding author, CAW, and housed at Louisiana State University. As per NSF guidelines, this material will be made publically accessible, and access and permission to use this associated data can be provided after a formal written request is received and accepted.

Supplemental Files

The supplemental files for this article can be found as follows:

- **Text S1.** Detailed description of 1) GIS and Landuse/Landcover analysis using Landsat and Google Earth imagery, 2) Bathymetry within channels, and 3) Calculations of tidal prism and sediment infilling. Includes Supplemental Figures S1–S4, and Supplemental Tables S1–S2. (PDF). DOI: https://doi.org/10.1525/elementa.263.s1
- **Figure S1.** Raw Landsat imagery from selected study areas for years 1973 and 2013, and same imagery with creek (unobstructed tidal channel, obstructed tidal channel 'khas land') and polder (embankments) shapefiles delineated. (PDF). DOI: https://doi.org/10.1525/elementa.263.s1
- **Figure S2.** dSVD imagery (which demarks change in land cover) within area P1and the Sundarbans forest is presented, exhibiting infilling in the polder region from 1989–2010 (manifested as transition from water to semi-wet land). In contrast, channel infilling is not prevalent in the Sundarbans, yet lateral migration within tidal channels is common (manifested as change in vegetated area to/from water). (PDF). DOI: https://doi.org/10.1525/elementa.263.s1
- **Figure S3.** Bathymetry survey results from Polder #32 tidal channels (PDF). DOI: https://doi.org/10.1525/elementa.263.s1
- **Figure S4.** Core stratigraphy and sediment grain size in a khas land channel is presented (PDF). DOI: https://doi.org/10.1525/elementa.263.s1
- **Table S1.** Detailed GIS results for 6 study areas in southwest Bangladesh (see Figure 3 for locations) (PDF). DOI: https://doi.org/10.1525/elementa.263.s1
- **Table S2.** Detailed tidal prism and sediment volume calculations are presented (PDF). DOI: https://doi.org/10.1525/elementa.263.s1
- **Dataset S1.** Tidal creek (1973, 2003, 2013) and polder embankment (2005) Shapefiles (SHP, ZIP). DOI: https://doi.org/10.1525/elementa.263.s1

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: CAW, SLG, JMG, CS
- Contributed to acquisition of data: CAW, CS, SS, RPH
- Contributed to analysis and interpretation of data: CAW, SLG, JMG, CS, SS, BM, RPH
- Drafted and/or revised the article: CAW, SLG, JMG, CS, BM, RPH
- Approved the submitted version for publication: CAW, SLG, JMG, CS, SS, BM, RPH

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