Intended vs unintended consequences of modifying coastal river channels

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Abstract

Capital works projects, particularly the modification of coastal rivers, are becoming increasingly significant to economic activities worldwide as a response to climate-driven changes and urbanization. The benefits of channel modification projects can be realized quickly, but the altered movement of sediments in the river channel can lead to unintended morphologic changes decades later. An example of this is the closure of the San Bernard River mouth, located on the central coast of Texas, which was clogged by sediments in the 1990s as a result of two major projects in the area: the diversion of the Brazos River channel (1929) and the construction of the Gulf Intracoastal Waterway (GIWW) (1940s). The objective of this study was to document the delayed geomorphic response to the projects using historical aerial imagery and provide a snapshot of flow pathways in the area using measurements collected in situ. Results showed that the GIWW was the main conduit for river flow as it bisects the San Bernard 2 km inland of its river mouth, reducing discharge in the terminal limb of the river. Due to reduced flow, the river mouth became clogged with wave-transported sediment supplied the Brazos River which had been diverted to within 6 km of the San Bernard. With no connection to the sea, altered sediment and flow pathways have led to numerous hazards and costly corrective dredging projects. To optimize the cost-effectiveness of channel modification projects their long-term impact must be considered as managers continue to adapt to ever-changing coastal zones.

Intended vs unintended consequences of modifying coastal river channels

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Key Points:

- To optimize the cost-benefit framework of coastal infrastructure projects, long-term impacts on sediment transport fields must be considered
- The San Bernard river mouth has been clogged by coastal sediments several decades after two channel modifications, creating costly problems
- The evolution of this river system provides an example of the delayed geomorphic consequences of man-made perturbations to coastal channels

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Abstract

Capital works projects, particularly the modification of coastal rivers, are becoming increasingly significant to economic activities worldwide as a response to climate-driven changes and urbanization. The benefits of channel modification projects can be realized quickly, but the altered movement of sediments in the river channel can lead to unintended morphologic changes decades later. An example of this is the closure of the San Bernard River mouth, located on the central coast of Texas, which was clogged by sediments in the 1990s as a result of two major projects in the area: the diversion of the Brazos River channel (1929) and the construction of the Gulf Intracoastal Waterway (GIWW) (1940s). The objective of this study was to document the delayed geomorphic response to the projects using historical aerial imagery and provide a snapshot of flow pathways in the area using measurements collected *in situ*. Results showed that the GIWW was the main conduit for river flow as it bisects the San Bernard 2 km inland of its river mouth, reducing discharge in the terminal limb of the river. Due to reduced flow, the river mouth became clogged with wave-transported sediment supplied the Brazos River which had been diverted to within 6 km of the San Bernard. With no connection to the sea, altered sediment and flow pathways have led to numerous hazards and costly corrective dredging projects. To optimize the cost-effectiveness of channel modification projects their long-term impact must be considered as managers continue to adapt to ever-changing coastal zones.

Coastal infrastructure projects such as channel re-routing, canal construction, and dredging can create quick solutions and benefits to economies worldwide. These projects can be expected to become more prominent in the future as climate change and urbanization continue to alter coastal zones. However, the difference in timescales between the transport of water and the resultant transport of sediments can lead to delayed geomorphic consequences. In this study we documented the evolution of the San Bernard River mouth, on the coast of Texas, which was clogged by sediments in the 1990's as a result of two major capital works projects completed decades earlier. We found that sediments supplied by the re-routed Brazos river were transported by waves to the river mouth and led to its closure. Furthermore, the construction of the Gulf Intracoastal Waterway, a barge canal that bisects the San Bernard, diverts river flow into the canal which reduces the ability of the river to sustain its own mouth. As a result, the closed river mouth has created numerous hazards and led to corrective dredging projects surpassing \$12 million. This river system illustrates the importance of considering long-term changes to sediment transport dynamics when altering coastal river systems.

1 Introduction

Fluvial-coastal transition zones are geomorphically dynamic areas that are beneficial to both coastal economies and the environment (Reguero et al., 2014). Climate-driven stressors and urban development are expected to increase vulnerability along coastlines throughout the world, making the interactions between natural and engineered processes increasingly important to address (Davis et al., 2018; Marsooli et al., 2019). Modifications to coastal rivers have been implemented to protect communities and infrastructure from environmental hazards and increase economic activity. However, these systems are often built to make the coastal zone rigid and stable (held in place by levees, channel diversions, dredges, hard shorelines, locks, etc.), in direct conflict with a landscape that is naturally mobile and defined by morphologic change. Furthermore, these engineering projects tend to be focused on short-term, local changes that provide immediate socioeconomic benefit, but can lead to long-term, regional perturbations that prove costly and hazardous.

Central to these unintended consequences is the difference timescales of hydrodynamics, the transport of fluids, and the resultant morphologic adjustment driven by the transport of sediments (Roelvink, 2006). Hydrodynamics occur on a much shorter timescale than morphologic change (minutes to hours for wind-driven and tidal flows, for example), so modifying the behavior of a channel results in a quick realization of the project goal. However, coupled with hydrodynamics is the transport of sediments and the resultant morphologic evolution which occurs on timescales which are orders of magnitude greater than that of the flow of water.

Examples of delayed geomorphic responses to capital works projects can be seen in many different coastal settings, such as the sand spit at the Senegal River mouth (Ndour et al., 2018), Santa Barbara harbor (Barnard et al., 2009), Kaituna river diversion (Flatley et al., 2018), and the avulsion of an engineered river channel in the Peace-Athabascan River delta in Canada (Wang et al., 2022). Across these examples spans the central theme of delayed geomorphic consequences stemming from an abrupt modification to the hydrodynamics of a system.

In this study we focused on the unintended coupling of the San Bernard and Brazos coastal river systems in Texas, USA to provide a detailed example that engineering for rigidity and short-term benefits can lead to delayed geomorphic hazards because of this difference. Today, the mouth of the San Bernard River, located 12 km southwest of Freeport, Texas (Fig. 1), is clogged with sediment as an unintended consequence of several engineering projects implemented over the last century. In 1929 the US Army Corps of Engineers diverted the lowermost 10 km of the Brazos River to a location 10 km southwest of its natural mouth in order to construct the Port of Freeport. A new Brazos River delta began to grow and encroach on the mouth of the San Bernard River which was now only 6 km down drift, providing excess sediments up-drift of the San Bernard River mouth. Furthermore, the Gulf Intracoastal Waterway (GIWW), constructed in the 1940s, runs parallel to the shoreline 2 km inland of the coast and intersects the San Bernard River. Flow from the San Bernard River was disrupted at the intersection which effectively added two artificial distributary to the coastal reach of the San Bernard river. Prior to 1929, mouths of the Brazos and San Bernard rivers were separated by a sufficient distance that one did not affect the other. By the late 1990's the San Bernard River mouth became clogged with sediments several decades after the modifications to nearby channels, establishing a new morphodynamic equilibrium of the now-linked coastal river systems. After two abrupt hydrodynamic changes to the river channels, the system took several decades to adjust and begin to experience negative impacts (Fig. 2).

Several negative impacts have arisen because of the clogging of the San Bernard River mouth. Enhanced backwater flooding during storm events (Sanchez & Parchure, 2001), especially during Hurricane Harvey in 2017, severely damaged coastal communities and infrastructure nearby (Blake & Zelinsky, 2017). Currents in the GIWW frequently create hazards for barge traffic (Sanchez & Parchure, 2001; Texas Department of Transportation, 2006), and deposition of fluvial sediments in the GIWW results in costly maintenance dredging (Hamilton et al., 2021). Nearby estuaries have also become fresher as a result of the lost connection to the sea (Kraus & Lin, 2002) which can negatively impact estuarine ecology (Palmer et al., 2011). As a result, the closing of the San Bernard has led to much publicity from local residents, industry, and coastal engineers regarding possible solutions.

Here we present a general overview of the history, impacts, and present morphodynamic processes influencing this unique fluvial-coastal transition. Coastal morphodynamics impact sizable portions of the global population and economies (Nicholls et al., 2007), and the need for sensible infrastructure is expected to increase as a result of climate-driven environmental changes to coastlines (Davis et al., 2018). Though the dynamics of this system are well known by local residents and coastal engineers, little attention has yet been paid to this instance of unintended negative consequences of coastal infrastructure from the broader scientific community. Furthermore, this case study shows that delayed geomorphic responses to channel modifications can lead to costly hazards decades later. To optimize the cost-benefit framework of coastal projects, changes to the hydrodynamic *and* sediment-transport fields must be considered at long-term and regional scales.

2 Background

The system began as two naturally independent coastal rivers and became a coupled, morphodynamically complex system after the two major modifications to their flow pathways. For decades after the diversion of the Brazos River (1929) and construction of the GIWW (1941), the two river systems appeared to be independent and stable. However, throughout the decades between 1941 and 1975, the sediment transport field was still adjusting to the channel modifications as Brazos delta sediments were being transported towards the mouth of the San Bernard River by wave-driven alongshore transport. This period of morphologic "stability" was interrupted in 1975 when the growing Brazos River delta began to deposit sediments on the eastern flank of the San Bernard, building a spit that began to pinch the river mouth (Fig. 2). By the year 2000, the coastal limb of the San Bernard River had steered parallel to the shoreline, tapered, and lost its connection with the Gulf of Mexico entirely, creating a new morphodynamic equilibrium and a now-linked coastal system. The decades-long lag time between the initial perturbations to the system and the achievement of equilibrium illustrates the flawed approach often taken by coastal managers, where a short-term, localized engineering solution often results in a long-term, regional shift in the morphodynamics of the system.

Both the San Bernard River and Brazos River drain into the Gulf of Mexico near Freeport, TX, located on the central Texas coast due south of Houston. The San Bernard River is 168 km long, laying between the basins of the Colorado River to the west and the Brazos to the east. Its small drainage basin (4,791 km^2) produces a flow that is driven mainly by local storms, and the resultant sediment discharge is small (Kraus & Lin, 2002). In contrast, the Brazos River is 1352 km long and drains a basin encompassing 115,565 km^2, including swathes of Texas and New Mexico. Flow and sediment discharge of the Brazos leads all Texas rivers, with an average annual suspended sediment yield estimated to be near 40 metric tons per km^2 (Rodriguez et al., 2000). At the Brazos River delta, wind-driven waves typically approach the shore from the southeast and drive strongly asymmetrical alongshore transport of beach sediments to the southwest. The prevailing wave climate typically drives alongshore transport of coastal and Brazos River sediments to the southwest, towards the San Bernard River. These coastal sediments are frequently impacted by storms, with extratropical northers occurring approximately 15-20 times a year and hurricanes once every two years on average (Rodriguez et al., 2000). These storms produce strong winds and precipitation which results in reworking of the shoreline near the two rivers, making the landscape highly dynamic.

The diversion of the Brazos River channel in 1929 essentially moved the river delta, in it's entirety, to a new location in less than 33 years. After 1929, sediment supply to the artificially abandoned Brazos River delta halted abruptly and the delta was rapidly eroded by strongly asymmetric wave action over the next 20 years. Approximately 10 km^2 of old delta top were removed, as sediments were transferred from the old Brazos River delta to the new location where amalgamated beach ridges grew to form the new delta. When the sand supply from the old delta waned, growth of the new delta became episodic, as flooding events rapidly built ridges separated by inter-ridge lagoons representing periods of relative dormancy in between these periods of flooding (Rodriguez et al., 2000).

The construction of the GIWW in the 1940s also had an impact on the dynamics of the two rivers. At it's intersection of with the San Bernard River, the dredged channel has a width of approximately 38 m and depth of 4.5 to 6 m along the centerline of

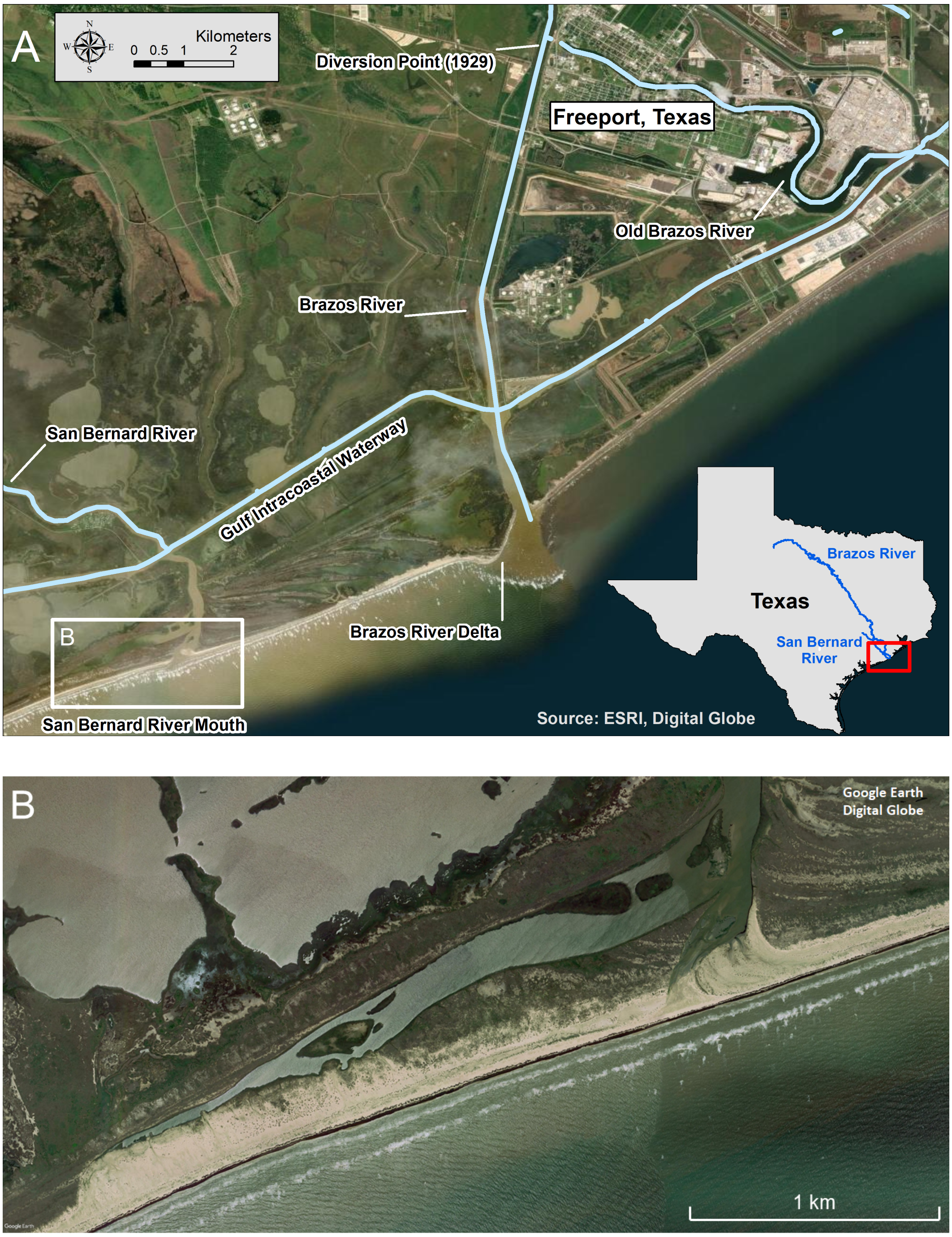

Figure 1. A) Vicinity map of the study area showing the Brazos River delta system and the San Bernard River. B) Aerial image of the closed mouth of the San Bernard River taken in 2014.

the canal in order to facilitate transport of goods by barge. This artificial bifurcation may partially divert flow of the San Bernard along the canal, reducing the ability of the main river channel to cut through accumulating foreshore and shoreface sediments and connect with the sea. State agencies like the Texas General Land Office and the US Army Corps of Engineers (USACE) have noted that the clogged river mouth has negative impacts on the flow regime of the area, resulting in problematic currents in the GIWW. Locks on either side of the Brazos River at the intersection with the GIWW were installed to prevent the GIWW from altering currents in the Brazos which aids navigation of barges in the area. These locks also serve to reduce sediment from the Brazos being deposited in the GIWW, mitigating the need for costly maintenance dredging. The altered San Bernard river flows result in problems for barges trying to cross the west locks of the Brazos due a buildup of water on the west side of the lock. Runoff from the San Bernard appears to flow through the GIWW rather than into the sea, creating a current that meets barges trying to pass through the locks and travel towards the San Bernard (Texas Department of Transportation, 2006). When crossing through the locks, barges are met with a bulge of water that often submerges their bow as the current pushes against it. This hazard has led to dredging efforts that have proven futile by the sand quickly reclogging the open river mouth, including a 2009 dredge in which the mouth was filled within 4 years. However, the dredging temporarily fixed the current issues in the GIWW and created a notable improvement in the ecology in the area that was praised by local fishermen (Callahan, 2016).

In addition to the current creating hazards for barges, the lost connection to the sea results in the estuary consisting of primarily freshwater, with the West Brazos lock and clogged river mouth eliminating presence of tidal saltwater (Kraus & Lin, 2002). Reopening the river mouth restores tidal inflow and the habitat of wetland species as well as solving the barge traffic problem at the West Brazos lock. The clogging of the San Bernard River mouth has generated a substantial amount of public interest as the community organization 'Friends of the River San Bernard' has lobbied and raised funds to dredge out the sand. This has led to public support of future dredging efforts, but the expense and futility of past projects has halted progress.

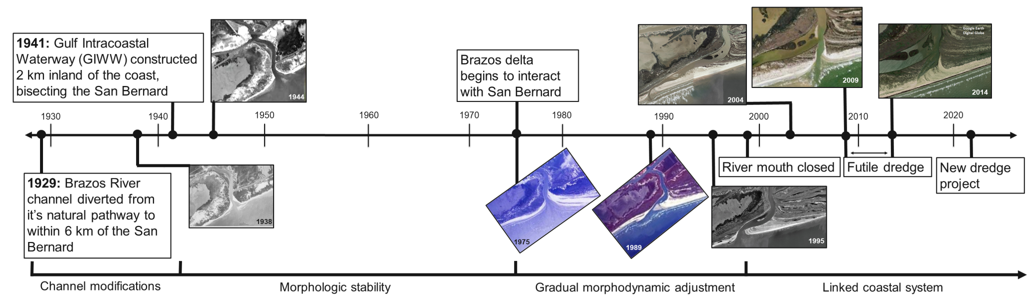

Figure 2. Annotated timeline that shows the key anthropogenic and geomorphic events that led to the coupling of the San Bernard and Brazos river coastal systems.

3 Methods

To adequately address the causes and consequences of the closed San Bernard River mouth, the impact of both the Brazos River diversion and GIWW construction were analyzed in this study. The development of the Brazos delta was documented using aerial images, historical nautical maps, and LiDAR scans taken from the publicly available Texas Natural Resources Information System (TNRIS) repository and Google Earth. A timeline of these images and maps show the growth of the relocated Brazos delta, its encroachment on the San Bernard, and the geomorphic processes that shape this stretch of the coast. Furthermore, bathymetric surveys conducted by the USACE over recent years were analyzed to reveal flow and sedimentation dynamics of the intersection of the San Bernard channel and the GIWW.

A secondary objective of this study was to provide a snapshot of calm-weather flow conditions of the intersection of the San Bernard River and GIWW. Flow data (direction and magnitude of water flux) were collected using a surfboard-mounted Sontek ADCP profiler. The survey was conducted during low discharge conditions in the summer. Water flux is calculated by multiplying the depth-averaged flow velocity by the channel depth for each reading, resulting in units of m^2/s. To minimize backwater effects from tidal flows, data were collected during an outgoing tide. Measurements were taken in transects along and across the San Bernard channel both upstream and downstream of its intersection with the GIWW, and along the GIWW East and West of the intersection. Flow measurements at the intersection were taken during a period of low discharge in the summer of 2021. At USGS station 08117705 at Sweeny, Texas, river discharge was less than 23 cubic meters per second and the water level was controlled by the outgoing tide. A simple analysis of flow direction and magnitude is reported here to yield a basic understanding of the flow field at the intersection and in the relatively abandoned limb of the San Bernard.

4 Results

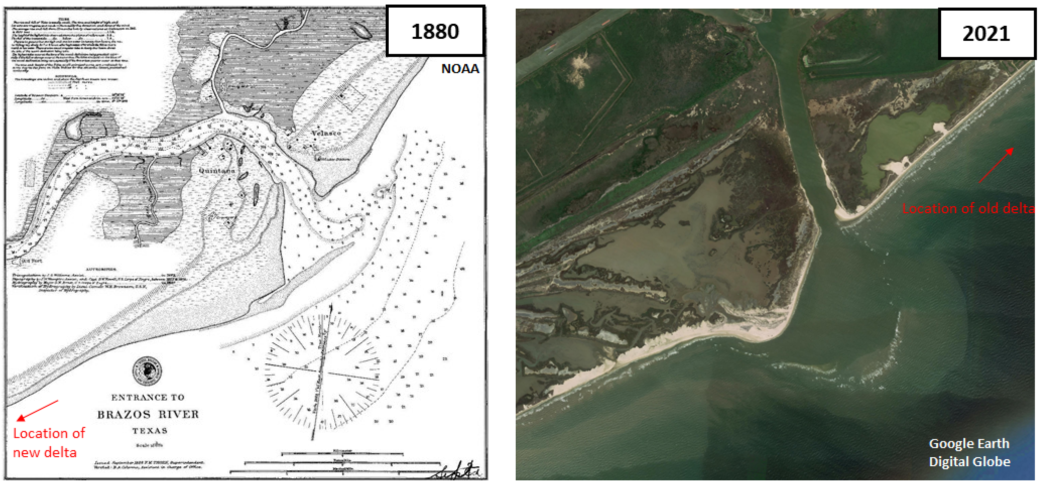

Figure 3. A nautical map from 1880 shows the natural Brazos River before installation of jetties and diversion in 1929. An aerial image from 2021 shows the new position of the Brazos delta 9 km southwest of the old delta. The morphology of both deltas are similar as a result of similar coastal sediment transport processes.

4.1 Evolution of the Brazos River delta

Aerial imagery and historical maps show that the San Bernard River mouth has been influenced by the nearby Brazos delta since the Brazos was diverted from its natural pathway in 1929. To understand the interactions between these two rivers, their significant difference in discharge must be considered. The diversion of the Brazos channel essentially placed a much larger river adjacent to the mouth of the San Bernard. Furthermore, with the GIWW potentially capturing a portion of the San Bernard River flow, the San Bernard became unable to overcome the buildup of sediment at its mouth.

To understand the evolution of the San Bernard River, the genesis and growth of the Brazos River delta must first be considered. Prior to the 1929 diversion of the Brazos River channel, the Brazos delta lay 10 km to the northeast of its present position. Nautical maps dating back to the 19^{th} century show that the morphology of the original Brazos River delta is similar to what is seen today (Fig. 3). The natural Brazos River delta featured a cuspate shape and submerged channel bar on the western flank of the river mouth as a result of the predominant direction of alongshore transport by waves. The cuspate shape of the delta, combined with the insignificance of tides on sediment transport on the Texas coast (Kraus & Lin, 2002) results in the dominance of waves on the delta shape (Nienhuis et al., 2015; Ashton & Giosan, 2011). After the main channel was diverted in 1929 a new delta began to form while sediments from the old abandoned delta was eroded away by wave action (Rodriguez et al., 2000). This new Brazos River delta, presently located between the Freeport, TX and the San Bernard River mouth, is geomorphorphically similar to its old form (Fig. 3). The east flank lies updrift of the river mouth and is composed of littoral sediments reworked into amalgamated ridges. On the other hand west flank is primarily controlled by fluvial sediment deposited into ridges and lagoons during flood events (Rodriguez et al 2000). The western flank of the delta presently undergoes the most significant and rapid growth.

As shown in Figure 4, the evolution of the delta can be separated two categories: one characterized by wave-driven reworking of during period of relatively calm weather, and another driven by construction of beach ridges during major flood events. Between 1929 and 1941, sand supplied by the rapidly eroding old delta along with river sediment from the Brazos led to rapid development a low-lying delta plain (Rodriguez et al., 2000). When the supply of old delta sediment slowed and stopped the growth of the new delta became episodic and dynamic as the control on its morphology shifted from wave-dominated alongshore transport of abandoned delta sediments to infrequent flooding events leading to rapid periods of growth. Major floods in 1941, 1957, 1965, and 1992 produced spikes in sediment discharge that led to accretion of channel mouth bars, construction of beach ridges, and progradation of the delta (Carlin & Delapenna, 2014). These flooding events occurred after long periods of drought, where the drainage basin was thought to be preconditioned for erosion of sediments that led to the growth of geomorphic features on the Brazos Delta (Fraticelli, 2006). Periods of growth during and after floods were characterized by growth of a channel bar and resultant formation of a back bar lagoon on the west flank. These channel mouth bars were then reworked into beach ridges. Alternating ridges and lagoons that are signatures of this flood-dominated morphology (Fig. 4). Between 1969 and 1992 a series of beach ridges were constructed and amalgamated by waves in absence of a flooding event capable of constructing a single sizable ride. It was during this period that the prograding Brazos delta began to encroach on the mouth of the San Bernard, eventually contributing enough sediment to fill the mouth completely.

4.2 Evolution of the San Bernard River mouth

Prior to the diversion of the Brazos River and the construction of the GIWW, the San Bernard River flowed into the Gulf of Mexico, with its channel oriented more or less perpendicular to the coast. Aerial images in Figure 5 show evolution of the Brazos delta and the interactions with the San Bernard. As early as 1938 the river mouth showed evidence of narrowing and channel steering by the growing Brazos delta. After approximately 30 years, the alluvial ridges of the Brazos delta had begun to encroach on the river mouth of the San Bernard in 1975, steering the river channel downdrift and tapering the width of the mouth. Spit accretion occurred on the updrift flank of the river mouth through the 1980's and 90's. Ebb-tidal islands appear in the 1987 image, a depositional pattern commonly seen in wave-dominated systems (Nienhuis et al., 2016). Steering and taper-

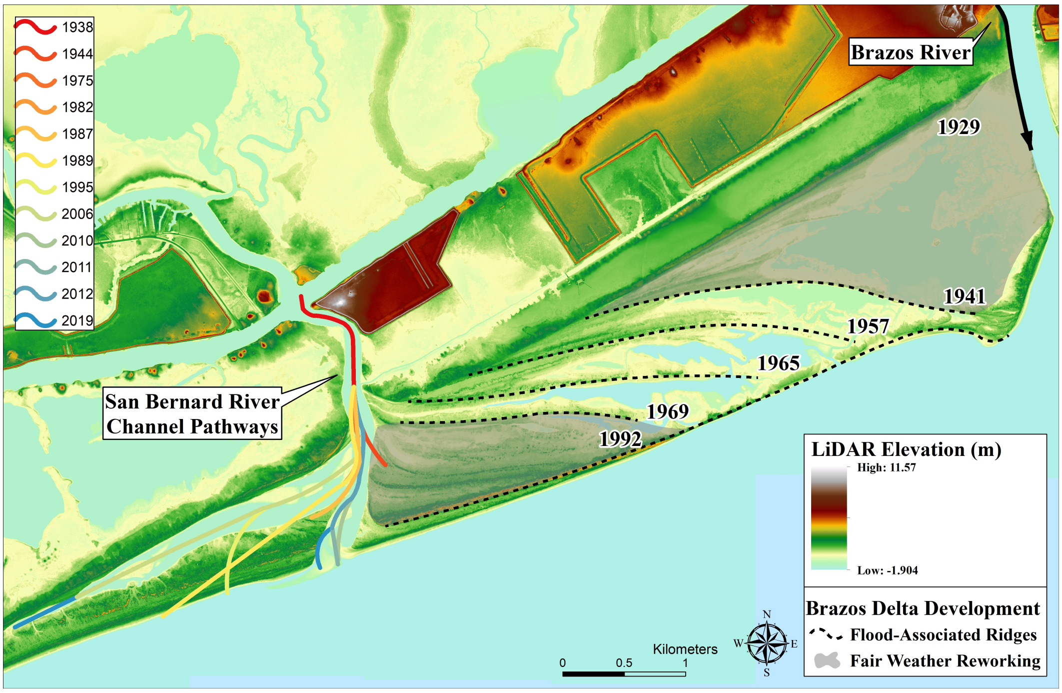

Figure 4. The coupled evolution of the Brazos River delta and the San Bernard River is shown atop a LiDAR-sourced digital elevation model. The chronology of the Brazos delta development is shown by gray areas that represent wave-driven reworking of sediments and black dotted lines that indicate rhythmic beach ridges constructed by geomorphically significant flood events (adapted from Rodriguez et al., 2000). Colorful lines show the pathways of the terminal stretch of the San Bernard River channel through time, where the growth of the Brazos delta steered and closed the San Bernard channel.

Figure 5. Aerial images showing the development of the Brazos delta and the subsequent alterations to the San Bernard River mouth.

ing of the channel occurred until the mid 2000's when the river mouth had completely closed, shutting off all connection with the Gulf of Mexico.

It is not uncommon for coastal river discharge to "compete" with strong wave-driven transport of beach sediments at the river mouth. Nienhuis et al. (2016) suggest that channels discharging onto wave-dominated coasts migrate downdrift when there is a) significant littoral transport and b) bypassing of sediments across the river mouth is limited. Typically, rivers will steer alongshore until the river outlet has sufficient discharge to maintain a permanent river mouth (Nienhuis et al., 2015). However, the San Bernard lacks the discharge required to maintain its own river mouth given the excess supply of beach sediments from the Brazos river delta, a problem exacerbated by the artificial distributary channels of the GIWW potentially reducing flow down the main San Bernard channel.

It is not uncommon for small river channels to flow onto wave-dominated coastlines with strong transport of beach sediments. Similar morphodynamic processes have been observed in absence of major engineering projects on the wave-dominated coast of North Canterbury, New Zealand. On the North Canterbury Bight, a coastline characterized by coarse sediments and a strong wave climate, river mouths are impounded by elongated spits controlled by alongshore drift processes, creating lagoon systems known as 'hapua' (Paterson et al., 2001, Measures et al., 2020). Typically, river mouth channels are steered parallel to the coastline in the direction of littoral drift (Paterson et al., 2001), leading to an offset between the main river channel and mouth (Hart, 2009). Akin to the San Bernard River mouth, the Waimakariri river mouth channel was silted shut and enhanced backwater flooding motivated a successful dredging effort in 1930 (Boyle & May, 2011). Major flood events have been observed to increase lagoon erosion and potentially breach the river mouth bar, providing the river with an outlet to the sea (Measures et al., 2020; Paterson et al., 2001). However, the proximity of the San Bernard to the Brazos River delta along with the bifurcation of it's channel by the GIWW provide both an excess of littoral sediments to accrete at the river mouth and an artifical pathway for San Bernard River flow. These unique circumstances have led to the San Bernard losing its connection with the sea entirely, contrary to the natural mechanisms by which a river mouth can "survive" in a wave dominated coast.

4.3 Influence of the GIWW on San Bernard River Flow

It has been well documented that the GIWW influences morphodynamic properties of features throughout the gulf coast. The GIWW has been known to carry sediment and interrupt flow from rivers it intersects, disrupting the typical conditions of the rivers (Swarzenski et al., 2003). Combined with the dynamics of the Brazos River and locks for barge traffic, flows in the study area are observed to be complex in both fair-weather and high-discharge conditions (Sanchez & Parchure, 2001).

We hypothesized that the artificial bifurcation created by the GIWW interrupts the San Bernard River flow, reducing river discharge as it flows toward the coast. In the natural world, bifurcation occurs as a result of the sediment transport and discharge characteristics of the main river channel. Deposition of sediments in a river channel leads to the construction of a bar which diverts flow until two distinct channels are present (Jerolmack & Swenson, 2007). Contrary to this natural process, the bifurcation of the San Bernard preceded the deposition of sediment at the river mouth. With the construction of the GIWW in the 1940's, sediment deposition at the river mouth became favorable (via sediments supplied by both the San Bernard and the Brazos Delta), completing the inverted sequence of bifurcation. This sequence was further complicated by the geometry of the GIWW, which served as the distributary channels of the San Bernard, as channels are dredged to a uniform depth (typically 12 ft) and width (125 ft) approximately every 18 months to facilitate barge traffic. Under natural conditions distributary channels typically have lesser channel widths and depths than the parent channel (Jerolmack & Swenson, 2007). Once again the opposite is true of the GIWW, further complicating the flow and depositional properties of the intersection.

Here we provide a simple snapshot of the flow characteristics at the intersection of the San Bernard river and the GIWW. Results showed that the principal conduit for flow in the study area was the GIWW, with peak flow velocities greater than 35 cm/s, and flow was weakest on the abandoned limb of the San Bernard channel (Fig. 6). Flow down the GIWW was directed westward, away from the Brazos River. The west Brazos locks were open, potentially allowing the Brazos River to drive these flows. Fluxes increased downstream of the intersection with the San Bernard River, and a perturbation in the flow direction along the GIWW suggests that the San Bernard River interrupts and enhances its westward flow.

In both the upstream and downstream portions of the San Bernard river, flows were directed seaward, with considerable directional spread due to the wind field at the time of sampling. Wind stress played a role in these data as our vessel was pushed around as the wind blew. Furthermore, small wind-waves were seen during gusts. Flow velocities in the San Bernard were generally lesser than those of the GIWW and were more readily manipulated by the wind. Flow speeds in the upstream limb of the San Bernard were generally between 10 and 20 cm/s. In the downstream limb of the San Bernard River the flow was subdued relative to its upper limb, with speeds up to 12 cm/s (Fig. 5).

Mean water fluxes, calculated by taking the average of measured flow velocities multiplied by channel depth, further highlight that the GIWW is the main conduit for flow in the system. The mean water flux for the GIWW was approximately 0.66 m^2/s, while the upstream limb of the San Bernard had a mean water flux of approximately 0.39 m^2/s. In contrast, shallow depths (typically < 2 m) and relatively low flow velocities yielded a mean water flux of 0.15 m^2/s in the downstream limb of the San Bernard. Thus, San

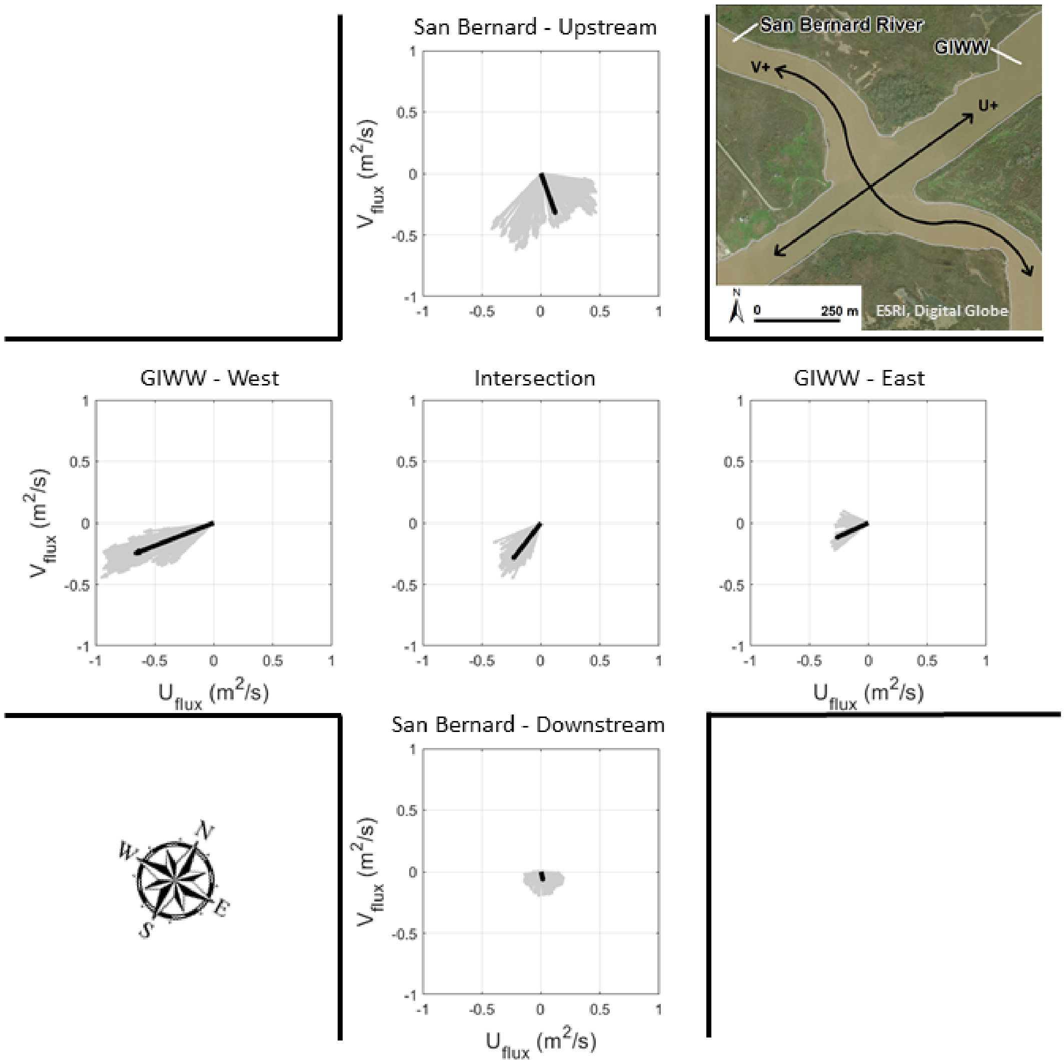

Figure 6. Observed directions and magnitudes of water flux at the intersection between the San Bernard and GIWW during calm-weather conditions show that the GIWW is the main conduit for flow of the system. San Bernard River contributes discharge to GIWW flow, leading to reduced velocities in the terminal limb of the channel downstream of the intersection. Mean water flux vectors shown in black, individual vectors shown in gray.

Bernard River flow appears to be captured more effectively by the GIWW rather than it's own downstream limb.

These results suggest that the San Bernard may play a tertiary role in the hydrodynamics of the area, behind the Brazos River and GIWW. In fair-weather conditions the San Bernard River system is controlled by coastal processes such as tides and flows from adjacent systems (the GIWW and Brazos River) rather than it's own discharge. Though the construction of the GIWW may have initially interrupted the flow of the San Bernard, the river now interrupts flow in the GIWW.

Figure 7. Series of aerial images that document the re-growth of the spit on the east flank of the San Bernard River mouth after being dredged open in 2009.

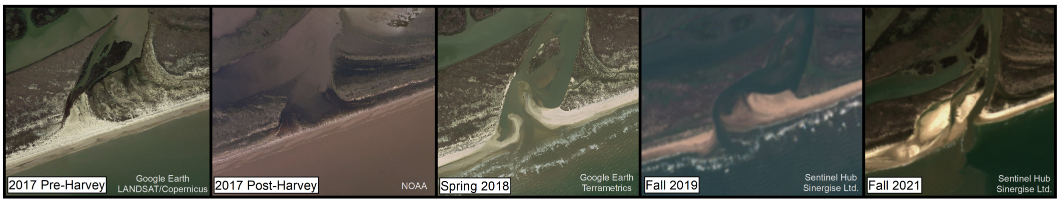

Figure 8. A series of aerial images show the brief breakthrough of the San Bernard River mouth after Hurricane Harvey flooding followed by formation of channel mouth bars and shallowing.

4.4 Futile Dredging of the San Bernard

A $2.4 million dredging project in 2010 removed 340,000 cubic yards of material from the San Bernard River mouth (Edwards, 2013), but within 4 years the cut was clogged once again. By 2011 beach sediments were reworked by wave action to form an elongated spit on the eastern flank of the artificial channel mouth. A series of amalgamated beach ridges began to form on the east side of the cut, narrowing and steering the channel clockwise until it was once again closed (Fig. 7). The dredged river mouth was closed by 2014 as a result of the same coastal processes that led to its initial closure in the late 1990's: a) accretion of a spit on the eastern flank by wave-driven transport of beach sediments, b) resultant steering of the San Bernard channel downdrift of it's dredged position, and c) tapering and closing of the river mouth. In 4-years the linked coastal rivers modified a man-made perturbation (the dredged channel) an order of magnitude faster than the previous response by the independent systems. This illustrates the control of wave-reworking of sediments on the river mouth in absence of a substantial flood event, such as a hurricane. Though the dredge provided short term benefits to the local ecology and GIWW currents (Edwards, 2013), a more substantial project must be implemented in order to permanently solve the problem.

4.5 Hurricane Harvey Impacts

In unengineered river systems an extreme storm is the primary mechanism to re-open a river mouth that is silted shut (Measures et al., 2020; Paterson et al., 2001). The landfall of Hurricane Harvey in late August of 2017 was a major flooding event that served as an extreme example of how the area responds to major flooding events. To better understand the dynamics of the area during these flooding episodes, aerial imagery and USACE bathymetric surveys taken shortly after Harvey help reveal what is happening to sediment and flow around the San Bernard. USGS gauge data reveals that the flooding experienced in the San Bernard created the highest stage ever recorded at that gauge, nearly 20 feet higher than the next closest flooding event. If the San Bernard was to ever gain enough erosive ability to cut through the sediment clogging its mouth, its strongest chance might have been during Hurricane Harvey.

Aerial images taken in the months after the hurricane reveal a brief breakthrough of the San Bernard River mouth due to the erosive ability of the floodwaters (Fig. 8). The flooding breached the ridges of the clogged river mouth at the location of the former natural and dredged channel mouths. The open channel has remained shallow and highly dynamic, with shoals and spits evolving on either side of the opening. A channel mouth bar on the eastern (updrift) flank of the river mouth had formed by December, and by March a similar bar formed on the western side. The nearly symmetrical bars are indicative of tidal reworking of beach sediments (Kraus & Lin, 2002). By the fall of 2019, an elongated spit on the eastern flank of the mouth has begun to steer the San Bernard channel to the southwest, tapering and closing the channel once again. The breach displayed geomorphic behavior similar to the life cycle of a tidal inlet, where spits on either side of the mouth waxed and waned according to littoral transport dynamics (Seminack & McBride, 2018). Orescanin et al., (2021) found that the dynamics of bar-built estuaries are controlled by the relationship between fluvial discharge and wave-driven alongshore transport of sediments. In the case of the San Bernard, the river mouth appears to be controlled by coastal processes (alongshore transport and tidal flushing) rather than fluvial discharge, thus leading to the closure of the river mouth.

4.6 Sedimentation of the Abandoned San Bernard Channel

The inactive San Bernard channel has remained relatively untouched by human activity, showing a buildup of sediment behind the clogged river mouth presumably due to reduced flow velocity at the intersection with the GIWW. Using USACE bathymetric surveys taken in June 2014 and April 2015, 10 months' worth of sedimentation are shown, typically between 20 and 50 cm with a maximum of 1 m. Depth values from both surveys were taken every 166 feet (50 m) from a 3500 foot (1066 m) transect running along the centerline of the inactive channel as defined by the USACE and plotted against each other (Fig. 8). Values spanning the width of the channel at interval were averaged and plotted, while the range of these values is shown in the bars. Rapid sedimentation in the inactive channel of the San Bernard is likely indicative of a reduction in water flux downstream of the intersection with the GIWW. Abrupt shallowing of the San Bernard channel downstream of the intersection may further divert river flow down the GIWW rather than towards the sea, promoting further deposition of sediments in the abandoned channel. Thus, the filling of the abandoned limb has likely worked in tandem with the accretion of beach sediments on the seaward side of the river mouth to reduce the probability of the San Bernard naturally reconnecting with the sea. Typically the shallowing and narrowing process continues as suspended sediments are deposited and erosion of the cut-bank is inhibited until the channel is completely filled (Toonen et al., 2012; Piegay et al., 2008). However, the San Bernard experiences massive flooding events such as Hurricane Harvey which may slow or eliminate this expected narrowing via erosion on the outer bank of the abandoned channel.

5 Discussion

5.1 Fate of the San Bernard

If the discharge and sediment of the San Bernard is not reaching the sea, it must be going somewhere else. Our results show that the GIWW may be the principal conduit for San Bernard River discharge rather than the terminal stem of its own channel. This suggests that the flow and sediment of the river is diverted into the canal rather than down its natural channel which allows the Brazos delta sediment to overpower and clog the mouth of the San Bernard. Documentation from numerous Texas government agencies also reveal flow travelling in the opposite direction in the northeast leg of the

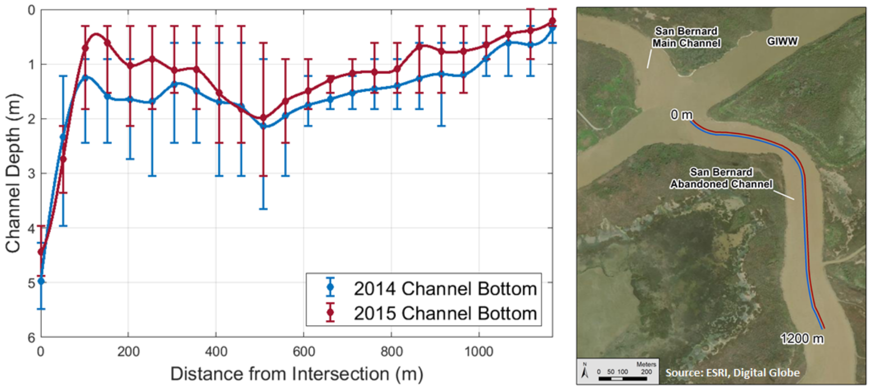

Figure 9. Bathymetric transects of the terminal limb of the San Bernard River in 2014 and 2015 show rapid accumulation of sediments throughout, suggesting reduced riverine flow promoting sediment deposition.

GIWW towards the west Brazos locks. These snapshots of the flow properties of the San Bernard could indicate that the GIWW acts as a 'T' shaped intersection, allowing runoff to travel in either direction along the GIWW rather than towards the sea.

If the San Bernard is ever to be restored to its natural state, ambitious and costly engineering projects are required. The two forces working against the San Bernard, flow down the GIWW instead of the main channel and Brazos sediment shoaling at the river mouth, must be addressed. As shown by the quick failure of the 2009 San Bernard dredging project, the longshore processes that transport Brazos sediment towards the mouth must be blocked by engineered structures or frequent maintenance dredging must be done in order to keep the mouth open. However, the diversion of flow at the intersection with the GIWW will continue to reduce flow volume and velocity down the terminal stretch of the San Bernard, leading to continued sedimentation.

Since 2018, governing institutions associated with the San Bernard have been working toward achieving a long-term solution, garnering strong public support. Beginning in July 2021 and completed in the spring of 2022, the "Mouth of the San Bernard River Restoration Project" was intended to permanently widen and deepen the San Bernard River mouth channel, enhancing the river's connection to the Gulf of Mexico. Material dredged in the abandoned channel was be used to replenish marsh habitat in the San Bernard Wildlife Refuge nearby (NOAA, 2021). Immediate benefits could include the reduction in flood hazard created by the backwater effect of the silted river mouth, calming of currents in the GIWW inhibiting barge traffic, and reduced sedimentation in the GIWW. Sediment buildup at the river mouth can be expected to continue as the long and shallow channel continues to display the tendency to close (Kraus & Lin, 2002).

This proposed project was more substantial and suggested a dredge that created a channel of 100 foot width and 10 foot depth stretching 1,800 feet into the Gulf of Mexico, requiring removal of 400,000 cubic yards of sand. In contrast to the dredging efforts of 2009, maintenance dredging will be performed every 3 – 5 years by the Port of Freeport to keep the river mouth free from excess sediment. Despite acknowledging continued sedimentation expected with this plan of action, the governing bodies have decided to move forward with the plan. Total cost estimates hover near \$10 million, with federal grant money being the source of funding. The Port of Freeport, Phillips 66, and Brazoria County have agreed to split the cost of maintenance dredging, which is estimated to cost \$2 million every few years (NOAA, 2021). Perhaps this recent push for the opening of the San Bernard will successfully alleviate the problems that have been persistent in the area for decades, but the longevity of this effort may not be cost effective. In fact, by October 2022 sedimentation has already made the outlet impassable to boat traffic as a result of low discharge over the previous summer (Holle, 2022). This highlights the necessity of consistent maintenance dredging, and shows that a "rigid coastline" approach is inherently at odds with the linked-coastal system.

6 Conclusion

Despite initial economic benefits of modifying coastal river channels, the difference in timescales between hydrodynamic perturbations and geomorphic responses can result in decades-delayed hazards. In this study we provide an example of two coastal engineering projects that modified the coastal reaches of nearby rivers, leading to a delayed and unintended linkage of the two systems that proved costly and hazardous. The first project, completed in 1929, was the diversion of the Brazos river to create the Port of Freeport, Texas, and the second was the construction of the GIWW in 1941 to facilitate barge traffic, bisecting the San Bernard river at its terminal limb. Though these projects were significant additions to economic activity to the state of Texas and beyond, the decades-delayed geomorphic response of the system to these perturbations illustrates the need for long-term, regional thinking when making channel modifications near the coast.

We conducted a simple evaluation of the morphodynamic factors leading to the closure of the mouth of the San Bernard River. The closure of the natural pathway of the San Bernard River has had negative effects on barge traffic, march ecology, and flooding hazards. A unique combination of coastal engineering projects, the diversion of the Brazos River channel and the construction of the GIWW, led to the San Bernard River mouth being clogged with sediments and shutting off its connection with the Gulf of Mexico. By diverting the Brazos River channel 10 km closer to the San Bernard River in 1929, engineers facilitated the rapid growth of a new river delta which encroached on and clogged the San Bernard via wave-induced alongshore transport of delta sediments. Furthermore, the construction of the GIWW diverted San Bernard River flow down the canal rather than towards the sea, leading to reduced fluvial discharge at the river mouth. This elevated the relative importance of coastal processes (alongshore transport and tidal flushing) in controlling the morphology of the river mouth.

Thus, the San Bernard River plays a peripheral role in the morphodynamics of the river mouth. As a result of reduced fluvial discharge, the river mouth behaves more like an inlet of a bar-built estuary where tides, alongshore transport, and storms dictate the morphology of the system. Efforts to correct the closure of the river mouth by routine dredging operations are presently underway, but the long-term results are yet to be seen. The dynamics of this engineered river mouth shows the tendency of human engineering projects to create unforeseen consequences as natural processes behave differently under these altered conditions.

7 Data Availability

Data files are publicly available and stored digitally at the Texas Data Repository (doi:10.18738/T8/INCGRW). The files include the Matlab processing script for processing and plotting Figure 6, a snapshot of water fluxes in an intersection-adjusted coordinate system, along with the raw source data collected from surfboard mounted ADCP profiler.

8 Acknowledgements

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9 References

Ashton, A. D., Giosan, L. (2011). Wave-angle control of delta evolution. *Geophysical Research Letters*, 38(13), 1–6. https://doi.org/10.1029/2011GL047630

Blake, E. S., Zelinsky, D. A. (2017). National Hurricane Center Tropical Cycle Report: Hurricane Harvey. 2005, 1–77. https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf

Barnard, P. L., Revell, D. L., Hoover, D., Warrick, J., Brocatus, J., Draut, A. E., ... Ryan, H. F. (2009). Coastal processes study of Santa Barbara and Ventura counties, California. *US Geological Survey Open-File Report*, 1029, 926.

Boyle, T. (2011). An investigation into the southward migration of the Waimakariri River mouth. *Environment Canterbury.*

Carlin, J. A., Dellapenna, T. M. (2014). Event-driven deltaic sedimentation on a low-gradient, low-energy shelf: The Brazos River subaqueous delta, northwestern Gulf of Mexico. *Marine Geology*, 353, 21–30. https://doi.org/10.1016/j.margeo.2014.03.017

Callahan, E. (2016, February 5). Support flows in for San Bernard. *The Facts* https://thefacts.com/news/article_5a6295a2-422d-510d-a3af-68bf3f1e95a4.html

Davis, R. A., Elko, N., Wang, P. (2018). Managing the Gulf Coast Using Geology and Engineering. *Geological Society of America.*

Edwards, R. (2013, May 19). The San Bernard River Mouth – One Year After Opening. *Friends of the San Bernard.*

Flatley, A., Rutherfurd, I. D., Hardie, R. (2018). River channel relocation: Problems and prospects. *Water*, 10(10), 1360.

Fraticelli, C. M. (2006). Climate forcing in a wave-dominated delta: The effects of drought-flood cycles on delta progradation. *Journal of Sedimentary Research*, 76(9–10), 1067–1076. https://doi.org/10.2110/jsr.2006.097

Hamilton, P. B., Lin, L., Jones, S. W. (2021). Investigation for Shoaling Reduction Along the Gulf Intracoastal Waterway (GIWW) at Caney Creek, Sargent, Texas. *Engineer Research and Development Center (US).*

Hart, D. E. (2009). Morphodynamics of non-estuarine rivermouth lagoons on high-energy coasts. *Journal of Coastal Research*, SPEC. ISSUE 56, 1355–1359.

Holle, K. (2022). Silt happens: Drought already causing a return of San Bernard build-up. *The Facts* https://www.sanbernardriver.com/news_details.php?view=article&ref=archive&month=2&year=2016&id=773

Jerolmack, D. J., Swenson, J. B. (2007). Scaling relationships and evolution of distributary networks on wave-influenced deltas. *Geophysical Research Letters*, 34(23), 1–5. https://doi.org/10.1029/2007GL031823

Kraus, N. C., Lin, L. H. (2002). Coastal Processes Study of San Bernard River Mouth, Texas: Stability and Maintenance of Mouth (Vol. 2). US Army Corps of Engineers, Engineer Research and Development Center, *Coastal and Hydraulics Laboratory.*

Measures, R. J., Hart, D. E., Cochrane, T. A., Hicks, D. M. (2020). Processes controlling river-mouth lagoon dynamics on high-energy mixed sand and gravel coasts. *Marine Geology*, 420(April 2019), 106082. https://doi.org/10.1016/j.margeo.2019.106082

National Oceanic & Atmospheric Administration (2021). Mouth of the San Bernard River Restoration Project.

Ndour, A., Laïbi, R. A., Sadio, M., Degbe, C. G., Diaw, A. T., Oyédé, L. M., ... Sambou, H. (2018). Management strategies for coastal erosion problems in West Africa: analysis, issues, and constraints drawn from the examples of Senegal and Benin. *Ocean Coastal Management*, 156, 92-106.

Nicholls, R. J., Wong, P. P., Burket, V. R., Codignotto, J., Hay, J. E., McLean, R. F., Ragoonaden, S., Woodroffe, C. D. (2007). Coastal systems and low-lying areas. *Climate Change 2007: Impacts, Adaptation and Vulnerability.*, 315–356.

Orescanin, M. M., Coughlin, J., Young, W. R. (2021). Morphological response of variable river discharge and wave forcing at a bar-built estuary. *Estuarine, Coastal and Shelf Science*, 258(May), 107438. https://doi.org/10.1016/j.ecss.2021.107438

Palmer, T. A., Montagna, P. A., Pollack, J. B., Kalke, R. D., DeYoe, H. R. (2011). The role of freshwater inflow in lagoons, rivers, and bays. *Hydrobiologia*, 667(1), 49–67. https://doi.org/10.1007/s10750-011-0637-0

Paterson, A., Hume, T., Healy, T., August, E., Paterson, A., Humej, T., Healyf, T. (2001). River Mouth Morphodynamics on a Mixed Sand-Gravel Coast Symposium (2000), *CHALLENGES FOR THE 21ST CENTURY IN COASTAL SCIENCES , River Mouth Morphodynamics on a Mixed Sand-Gravel Coast.* 34, 288–294.

Piégay, H., Hupp, C. R., Citterio, A., Dufour, S., Moulin, B., Walling, D. E. (2008). Spatial and temporal variability in sedimentation rates associated with cutoff channel in-fill deposits: Ain River, France. *Water Resources Research*, 44(5), 1–18. https://doi.org/10.1029/2006WR005260

Reguero, B. G., Bresch, D. N., Beck, M., Calil, J., Meliane, I. (2014). Coastal risks, nature-based defenses and the economics of adaptation: An application in the Gulf of Mexico, USA. *Coastal Engineering Proceedings*, 1(34), 25.

Rodriguez, A. B., Hamilton, M. D., Anderson, J. B. (2000). Facies and evolution of the modern brazos delta, texas: Wave versus flood influence. *Journal of Sedimentary Research*, 70(2), 283–295. https://doi.org/10.1306/2DC40911-0E47-11D7-8643000102C1865D

Roelvink, J. A. (2006). Coastal morphodynamic evolution techniques. *Coastal engineering*, 53(2-3), 277-287.

Seminack, C. T., McBride, R. A. (2018). A life-cycle model for wave-dominated tidal inlets along passive margin coasts of North America. *Geomorphology*, 304, 141–158. https://doi.org/10.1016/j.geomorph.2017.12.038

Stewart, Richard. (2009, January 18). Workers will dredge new mouth for San Bernard River. *Houston Chronicle*, 1–5.

Swarzenski, C. M. (2003). Surface-water hydrology of the Gulf Intracoastal Waterway in south-central Louisiana, 1996-99 (p. 51). *US Department of the Interior, US Geological Survey.*

Texas Department of Transportation. (2006). Gulf Intracoastal Waterway. *2005-2006 Legislative Report.*

Toonen, W. H., Kleinhans, M. G., Cohen, K. M. (2012). Sedimentary architecture of abandoned channel fills. *Earth surface processes and landforms*, 37(4), 459-472. https://doi.org/10.1002/esp.3189

Wang, B., Smith, L.C., Kyzivat, E.D., Fayne, J.V., Gleason, C.J., Langhorst, T., Harlan, M., Feng, D., Muñoz, S., Eidam, E. & Pavelsky, T. (2022, December). Tracking an ongoing river avulsion with satellite remote sensing and field measurements. *In Fall Meeting 2022. AGU.*

Wolfe, W. (2021, June 8). River Mouth Contract in Place San Bernard dredging could start in July. *The Facts Brazoria County.*

Intended vs unintended consequences of modifying coastal river channels

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Keywords: Coastal Infrastructure, Coupled Human-Natural Systems, Coastal Morphodynamics, Hydrodynamics, River Deltas, Sediment Transport

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Key Points:

- To optimize the cost-benefit framework of coastal infrastructure projects, long-term impacts on sediment transport fields must be considered
- The San Bernard river mouth has been clogged by coastal sediments several decades after two channel modifications, creating costly problems
- The evolution of this river system provides an example of the delayed geomorphic consequences of man-made perturbations to coastal channels

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Abstract

Capital works projects, particularly the modification of coastal rivers, are becoming increasingly significant to economic activities worldwide as a response to climate-driven changes and urbanization. The benefits of channel modification projects can be realized quickly, but the altered movement of sediments in the river channel can lead to unintended morphologic changes decades later. An example of this is the closure of the San Bernard River mouth, located on the central coast of Texas, which was clogged by sediments in the 1990s as a result of two major projects in the area: the diversion of the Brazos River channel (1929) and the construction of the Gulf Intracoastal Waterway (GIWW) (1940s). The objective of this study was to document the delayed geomorphic response to the projects using historical aerial imagery and provide a snapshot of flow pathways in the area using measurements collected *in situ*. Results showed that the GIWW was the main conduit for river flow as it bisects the San Bernard 2 km inland of its river mouth, reducing discharge in the terminal limb of the river. Due to reduced flow, the river mouth became clogged with wave-transported sediment supplied the Brazos River which had been diverted to within 6 km of the San Bernard. With no connection to the sea, altered sediment and flow pathways have led to numerous hazards and costly corrective dredging projects. To optimize the cost-effectiveness of channel modification projects their long-term impact must be considered as managers continue to adapt to ever-changing coastal zones.

Coastal infrastructure projects such as channel re-routing, canal construction, and dredging can create quick solutions and benefits to economies worldwide. These projects can be expected to become more prominent in the future as climate change and urbanization continue to alter coastal zones. However, the difference in timescales between the transport of water and the resultant transport of sediments can lead to delayed geomorphic consequences. In this study we documented the evolution of the San Bernard River mouth, on the coast of Texas, which was clogged by sediments in the 1990's as a result of two major capital works projects completed decades earlier. We found that sediments supplied by the re-routed Brazos river were transported by waves to the river mouth and led to its closure. Furthermore, the construction of the Gulf Intracoastal Waterway, a barge canal that bisects the San Bernard, diverts river flow into the canal which reduces the ability of the river to sustain its own mouth. As a result, the closed river mouth has created numerous hazards and led to corrective dredging projects surpassing $12 million. This river system illustrates the importance of considering long-term changes to sediment transport dynamics when altering coastal river systems.

1 Introduction

Fluvial-coastal transition zones are geomorphically dynamic areas that are beneficial to both coastal economies and the environment (Reguero et al., 2014). Climate-driven stressors and urban development are expected to increase vulnerability along coastlines throughout the world, making the interactions between natural and engineered processes increasingly important to address (Davis et al., 2018; Marsooli et al., 2019). Modifications to coastal rivers have been implemented to protect communities and infrastructure from environmental hazards and increase economic activity. However, these systems are often built to make the coastal zone rigid and stable (held in place by levees, channel diversions, dredges, hard shorelines, locks, etc.), in direct conflict with a landscape that is naturally mobile and defined by morphologic change. Furthermore, these engineering projects tend to be focused on short-term, local changes that provide immediate socioeconomic benefit, but can lead to long-term, regional perturbations that prove costly and hazardous.

Central to these unintended consequences is the difference timescales of hydrodynamics, the transport of fluids, and the resultant morphologic adjustment driven by the transport of sediments (Roelvink, 2006). Hydrodynamics occur on a much shorter timescale than morphologic change (minutes to hours for wind-driven and tidal flows, for example), so modifying the behavior of a channel results in a quick realization of the project goal. However, coupled with hydrodynamics is the transport of sediments and the resultant morphologic evolution which occurs on timescales which are orders of magnitude greater than that of the flow of water.

Examples of delayed geomorphic responses to capital works projects can be seen in many different coastal settings, such as the sand spit at the Senegal River mouth (Ndour et al., 2018), Santa Barbara harbor (Barnard et al., 2009), Kaituna river diversion (Flatley et al., 2018), and the avulsion of an engineered river channel in the Peace-Athabascan River delta in Canada (Wang et al., 2022). Across these examples spans the central theme of delayed geomorphic consequences stemming from an abrupt modification to the hydrodynamics of a system.

In this study we focused on the unintended coupling of the San Bernard and Brazos coastal river systems in Texas, USA to provide a detailed example that engineering for rigidity and short-term benefits can lead to delayed geomorphic hazards because of this difference. Today, the mouth of the San Bernard River, located 12 km southwest of Freeport, Texas (Fig. 1), is clogged with sediment as an unintended consequence of several engineering projects implemented over the last century. In 1929 the US Army Corps of Engineers diverted the lowermost 10 km of the Brazos River to a location 10 km southwest of its natural mouth in order to construct the Port of Freeport. A new Brazos River delta began to grow and encroach on the mouth of the San Bernard River which was now only 6 km down drift, providing excess sediments up-drift of the San Bernard River mouth. Furthermore, the Gulf Intracoastal Waterway (GIWW), constructed in the 1940s, runs parallel to the shoreline 2 km inland of the coast and intersects the San Bernard River. Flow from the San Bernard River was disrupted at the intersection which effectively added two artificial distributary to the coastal reach of the San Bernard river. Prior to 1929, mouths of the Brazos and San Bernard rivers were separated by a sufficient distance that one did not affect the other. By the late 1990's the San Bernard River mouth became clogged with sediments several decades after the modifications to nearby channels, establishing a new morphodynamic equilibrium of the now-linked coastal river systems. After two abrupt hydrodynamic changes to the river channels, the system took several decades to adjust and begin to experience negative impacts (Fig. 2).

Several negative impacts have arisen because of the clogging of the San Bernard River mouth. Enhanced backwater flooding during storm events (Sanchez & Parchure, 2001), especially during Hurricane Harvey in 2017, severely damaged coastal communities and infrastructure nearby (Blake & Zelinsky, 2017). Currents in the GIWW frequently create hazards for barge traffic (Sanchez & Parchure, 2001; Texas Department of Transportation, 2006), and deposition of fluvial sediments in the GIWW results in costly maintenance dredging (Hamilton et al., 2021). Nearby estuaries have also become fresher as a result of the lost connection to the sea (Kraus & Lin, 2002) which can negatively impact estuarine ecology (Palmer et al., 2011). As a result, the closing of the San Bernard has led to much publicity from local residents, industry, and coastal engineers regarding possible solutions.

Here we present a general overview of the history, impacts, and present morphodynamic processes influencing this unique fluvial-coastal transition. Coastal morphodynamics impact sizable portions of the global population and economies (Nicholls et al., 2007), and the need for sensible infrastructure is expected to increase as a result of climate-driven environmental changes to coastlines (Davis et al., 2018). Though the dynamics of this system are well known by local residents and coastal engineers, little attention has yet been paid to this instance of unintended negative consequences of coastal infrastructure from the broader scientific community. Furthermore, this case study shows that delayed geomorphic responses to channel modifications can lead to costly hazards decades later. To optimize the cost-benefit framework of coastal projects, changes to the hydrodynamic *and* sediment-transport fields must be considered at long-term and regional scales.

2 Background

The system began as two naturally independent coastal rivers and became a coupled, morphodynamically complex system after the two major modifications to their flow pathways. For decades after the diversion of the Brazos River (1929) and construction of the GIWW (1941), the two river systems appeared to be independent and stable. However, throughout the decades between 1941 and 1975, the sediment transport field was still adjusting to the channel modifications as Brazos delta sediments were being transported towards the mouth of the San Bernard River by wave-driven alongshore transport. This period of morphologic "stability" was interrupted in 1975 when the growing Brazos River delta began to deposit sediments on the eastern flank of the San Bernard, building a spit that began to pinch the river mouth (Fig. 2). By the year 2000, the coastal limb of the San Bernard River had steered parallel to the shoreline, tapered, and lost its connection with the Gulf of Mexico entirely, creating a new morphodynamic equilibrium and a now-linked coastal system. The decades-long lag time between the initial perturbations to the system and the achievement of equilibrium illustrates the flawed approach often taken by coastal managers, where a short-term, localized engineering solution often results in a long-term, regional shift in the morphodynamics of the system.

Both the San Bernard River and Brazos River drain into the Gulf of Mexico near Freeport, TX, located on the central Texas coast due south of Houston. The San Bernard River is 168 km long, laying between the basins of the Colorado River to the west and the Brazos to the east. Its small drainage basin (4,791 km^2) produces a flow that is driven mainly by local storms, and the resultant sediment discharge is small (Kraus & Lin, 2002). In contrast, the Brazos River is 1352 km long and drains a basin encompassing 115,565 km^2, including swathes of Texas and New Mexico. Flow and sediment discharge of the Brazos leads all Texas rivers, with an average annual suspended sediment yield estimated to be near 40 metric tons per km^2 (Rodriguez et al., 2000). At the Brazos River delta, wind-driven waves typically approach the shore from the southeast and drive strongly asymmetrical alongshore transport of beach sediments to the southwest. The prevailing wave climate typically drives alongshore transport of coastal and Brazos River sediments to the southwest, towards the San Bernard River. These coastal sediments are frequently impacted by storms, with extratropical northers occurring approximately 15-20 times a year and hurricanes once every two years on average (Rodriguez et al., 2000). These storms produce strong winds and precipitation which results in reworking of the shoreline near the two rivers, making the landscape highly dynamic.

The diversion of the Brazos River channel in 1929 essentially moved the river delta, in it's entirety, to a new location in less than 33 years. After 1929, sediment supply to the artificially abandoned Brazos River delta halted abruptly and the delta was rapidly eroded by strongly asymmetric wave action over the next 20 years. Approximately 10 km^2 of old delta top were removed, as sediments were transferred from the old Brazos River delta to the new location where amalgamated beach ridges grew to form the new delta. When the sand supply from the old delta waned, growth of the new delta became episodic, as flooding events rapidly built ridges separated by inter-ridge lagoons representing periods of relative dormancy in between these periods of flooding (Rodriguez et al., 2000).

The construction of the GIWW in the 1940s also had an impact on the dynamics of the two rivers. At it's intersection of with the San Bernard River, the dredged channel has a width of approximately 38 m and depth of 4.5 to 6 m along the centerline of

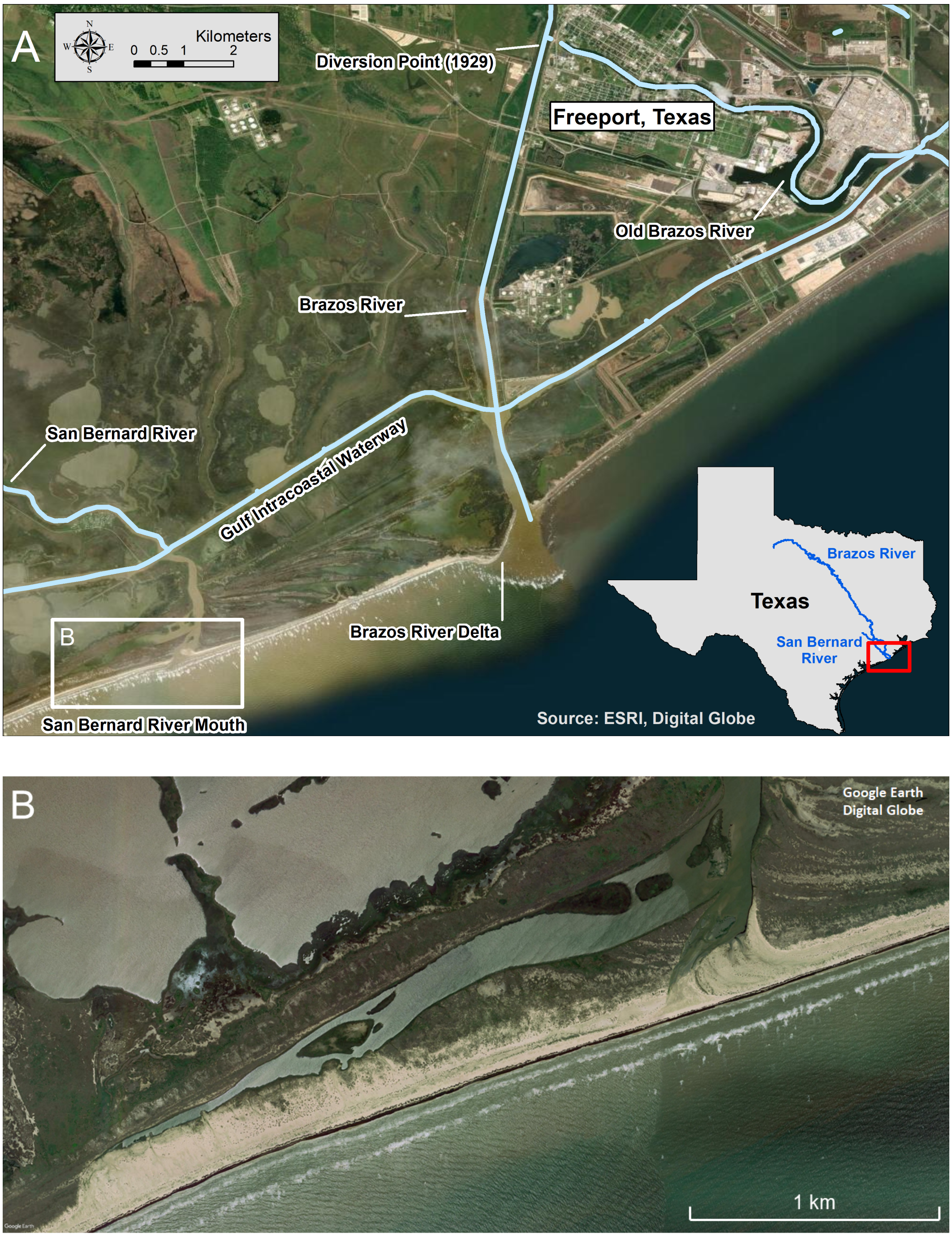

Figure 1. A) Vicinity map of the study area showing the Brazos River delta system and the San Bernard River. B) Aerial image of the closed mouth of the San Bernard River taken in 2014.

the canal in order to facilitate transport of goods by barge. This artificial bifurcation may partially divert flow of the San Bernard along the canal, reducing the ability of the main river channel to cut through accumulating foreshore and shoreface sediments and connect with the sea. State agencies like the Texas General Land Office and the US Army Corps of Engineers (USACE) have noted that the clogged river mouth has negative impacts on the flow regime of the area, resulting in problematic currents in the GIWW. Locks on either side of the Brazos River at the intersection with the GIWW were installed to prevent the GIWW from altering currents in the Brazos which aids navigation of barges in the area. These locks also serve to reduce sediment from the Brazos being deposited in the GIWW, mitigating the need for costly maintenance dredging. The altered San Bernard river flows result in problems for barges trying to cross the west locks of the Brazos due a buildup of water on the west side of the lock. Runoff from the San Bernard appears to flow through the GIWW rather than into the sea, creating a current that meets barges trying to pass through the locks and travel towards the San Bernard (Texas Department of Transportation, 2006). When crossing through the locks, barges are met with a bulge of water that often submerges their bow as the current pushes against it. This hazard has led to dredging efforts that have proven futile by the sand quickly reclogging the open river mouth, including a 2009 dredge in which the mouth was filled within 4 years. However, the dredging temporarily fixed the current issues in the GIWW and created a notable improvement in the ecology in the area that was praised by local fishermen (Callahan, 2016).

In addition to the current creating hazards for barges, the lost connection to the sea results in the estuary consisting of primarily freshwater, with the West Brazos lock and clogged river mouth eliminating presence of tidal saltwater (Kraus & Lin, 2002). Reopening the river mouth restores tidal inflow and the habitat of wetland species as well as solving the barge traffic problem at the West Brazos lock. The clogging of the San Bernard River mouth has generated a substantial amount of public interest as the community organization 'Friends of the River San Bernard' has lobbied and raised funds to dredge out the sand. This has led to public support of future dredging efforts, but the expense and futility of past projects has halted progress.

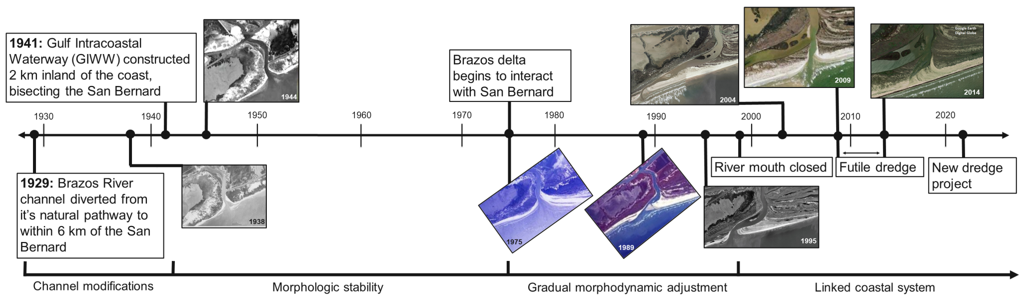

Figure 2. Annotated timeline that shows the key anthropogenic and geomorphic events that led to the coupling of the San Bernard and Brazos river coastal systems.

3 Methods

To adequately address the causes and consequences of the closed San Bernard River mouth, the impact of both the Brazos River diversion and GIWW construction were analyzed in this study. The development of the Brazos delta was documented using aerial images, historical nautical maps, and LiDAR scans taken from the publicly available Texas Natural Resources Information System (TNRIS) repository and Google Earth. A timeline of these images and maps show the growth of the relocated Brazos delta, its encroachment on the San Bernard, and the geomorphic processes that shape this stretch of the coast. Furthermore, bathymetric surveys conducted by the USACE over recent years were analyzed to reveal flow and sedimentation dynamics of the intersection of the San Bernard channel and the GIWW.

A secondary objective of this study was to provide a snapshot of calm-weather flow conditions of the intersection of the San Bernard River and GIWW. Flow data (direction and magnitude of water flux) were collected using a surfboard-mounted Sontek ADCP profiler. The survey was conducted during low discharge conditions in the summer. Water flux is calculated by multiplying the depth-averaged flow velocity by the channel depth for each reading, resulting in units of m^2/s. To minimize backwater effects from tidal flows, data were collected during an outgoing tide. Measurements were taken in transects along and across the San Bernard channel both upstream and downstream of its intersection with the GIWW, and along the GIWW East and West of the intersection. Flow measurements at the intersection were taken during a period of low discharge in the summer of 2021. At USGS station 08117705 at Sweeny, Texas, river discharge was less than 23 cubic meters per second and the water level was controlled by the outgoing tide. A simple analysis of flow direction and magnitude is reported here to yield a basic understanding of the flow field at the intersection and in the relatively abandoned limb of the San Bernard.

4 Results

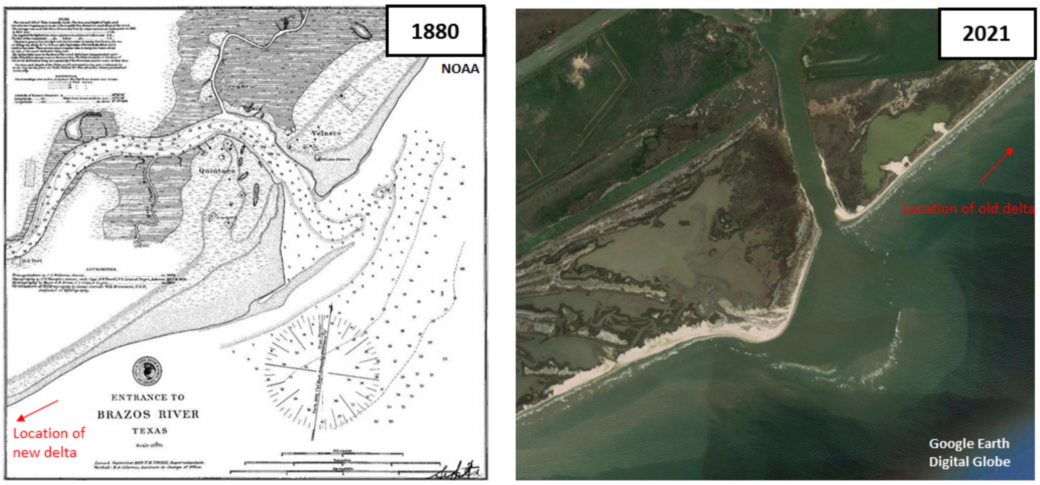

Figure 3. A nautical map from 1880 shows the natural Brazos River before installation of jetties and diversion in 1929. An aerial image from 2021 shows the new position of the Brazos delta 9 km southwest of the old delta. The morphology of both deltas are similar as a result of similar coastal sediment transport processes.

4.1 Evolution of the Brazos River delta

Aerial imagery and historical maps show that the San Bernard River mouth has been influenced by the nearby Brazos delta since the Brazos was diverted from its natural pathway in 1929. To understand the interactions between these two rivers, their significant difference in discharge must be considered. The diversion of the Brazos channel essentially placed a much larger river adjacent to the mouth of the San Bernard. Furthermore, with the GIWW potentially capturing a portion of the San Bernard River flow, the San Bernard became unable to overcome the buildup of sediment at its mouth.

To understand the evolution of the San Bernard River, the genesis and growth of the Brazos River delta must first be considered. Prior to the 1929 diversion of the Brazos River channel, the Brazos delta lay 10 km to the northeast of its present position. Nautical maps dating back to the 19th century show that the morphology of the original Brazos River delta is similar to what is seen today (Fig. 3). The natural Brazos River delta featured a cuspate shape and submerged channel bar on the western flank of the river mouth as a result of the predominant direction of alongshore transport by waves. The cuspate shape of the delta, combined with the insignificance of tides on sediment transport on the Texas coast (Kraus & Lin, 2002) results in the dominance of waves on the delta shape (Nienhuis et al., 2015; Ashton & Giosan, 2011). After the main channel was diverted in 1929 a new delta began to form while sediments from the old abandoned delta was eroded away by wave action (Rodriguez et al., 2000). This new Brazos River delta, presently located between the Freeport, TX and the San Bernard River mouth, is geomorphorphically similar to its old form (Fig. 3). The east flank lies updrift of the river mouth and is composed of littoral sediments reworked into amalgamated ridges. On the other hand west flank is primarily controlled by fluvial sediment deposited into ridges and lagoons during flood events (Rodriguez et al 2000). The western flank of the delta presently undergoes the most significant and rapid growth.

As shown in Figure 4, the evolution of the delta can be separated two categories: one characterized by wave-driven reworking of during period of relatively calm weather, and another driven by construction of beach ridges during major flood events. Between 1929 and 1941, sand supplied by the rapidly eroding old delta along with river sediment from the Brazos led to rapid development a low-lying delta plain (Rodriguez et al., 2000). When the supply of old delta sediment slowed and stopped the growth of the new delta became episodic and dynamic as the control on its morphology shifted from wave-dominated alongshore transport of abandoned delta sediments to infrequent flooding events leading to rapid periods of growth. Major floods in 1941, 1957, 1965, and 1992 produced spikes in sediment discharge that led to accretion of channel mouth bars, construction of beach ridges, and progradation of the delta (Carlin & Delapenna, 2014). These flooding events occurred after long periods of drought, where the drainage basin was thought to be preconditioned for erosion of sediments that led to the growth of geomorphic features on the Brazos Delta (Fraticelli, 2006). Periods of growth during and after floods were characterized by growth of a channel bar and resultant formation of a back bar lagoon on the west flank. These channel mouth bars were then reworked into beach ridges. Alternating ridges and lagoons that are signatures of this flood-dominated morphology (Fig. 4). Between 1969 and 1992 a series of beach ridges were constructed and amalgamated by waves in absence of a flooding event capable of constructing a single sizable ride. It was during this period that the prograding Brazos delta began to encroach on the mouth of the San Bernard, eventually contributing enough sediment to fill the mouth completely.

4.2 Evolution of the San Bernard River mouth

Prior to the diversion of the Brazos River and the construction of the GIWW, the San Bernard River flowed into the Gulf of Mexico, with its channel oriented more or less perpendicular to the coast. Aerial images in Figure 5 show evolution of the Brazos delta and the interactions with the San Bernard. As early as 1938 the river mouth showed evidence of narrowing and channel steering by the growing Brazos delta. After approximately 30 years, the alluvial ridges of the Brazos delta had begun to encroach on the river mouth of the San Bernard in 1975, steering the river channel downdrift and tapering the width of the mouth. Spit accretion occurred on the updrift flank of the river mouth through the 1980's and 90's. Ebb-tidal islands appear in the 1987 image, a depositional pattern commonly seen in wave-dominated systems (Nienhuis et al., 2016). Steering and taper-

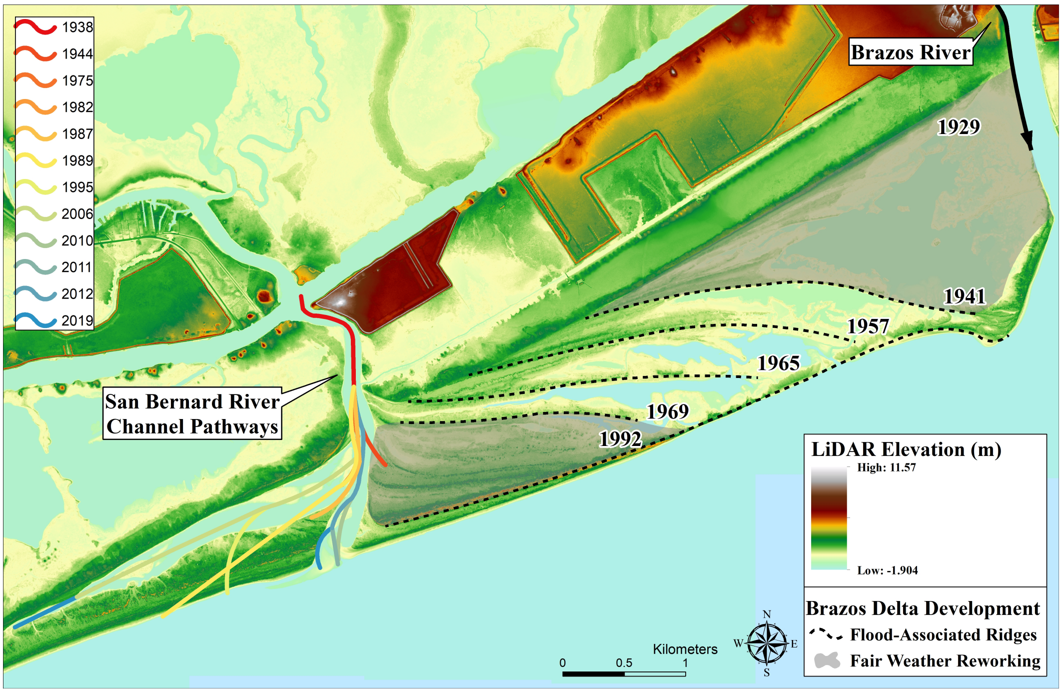

Figure 4. The coupled evolution of the Brazos River delta and the San Bernard River is shown atop a LiDAR-sourced digital elevation model. The chronology of the Brazos delta development is shown by gray areas that represent wave-driven reworking of sediments and black dotted lines that indicate rhythmic beach ridges constructed by geomorphically significant flood events (adapted from Rodriguez et al., 2000). Colorful lines show the pathways of the terminal stretch of the San Bernard River channel through time, where the growth of the Brazos delta steered and closed the San Bernard channel.

Figure 5. Aerial images showing the development of the Brazos delta and the subsequent alterations to the San Bernard River mouth.

ing of the channel occurred until the mid 2000's when the river mouth had completely closed, shutting off all connection with the Gulf of Mexico.

It is not uncommon for coastal river discharge to "compete" with strong wave-driven transport of beach sediments at the river mouth. Nienhuis et al. (2016) suggest that channels discharging onto wave-dominated coasts migrate downdrift when there is a) significant littoral transport and b) bypassing of sediments across the river mouth is limited. Typically, rivers will steer alongshore until the river outlet has sufficient discharge to maintain a permanent river mouth (Nienhuis et al., 2015). However, the San Bernard lacks the discharge required to maintain its own river mouth given the excess supply of beach sediments from the Brazos river delta, a problem exacerbated by the artificial distributary channels of the GIWW potentially reducing flow down the main San Bernard channel.

It is not uncommon for small river channels to flow onto wave-dominated coastlines with strong transport of beach sediments. Similar morphodynamic processes have been observed in absence of major engineering projects on the wave-dominated coast of North Canterbury, New Zealand. On the North Canterbury Bight, a coastline characterized by coarse sediments and a strong wave climate, river mouths are impounded by elongated spits controlled by alongshore drift processes, creating lagoon systems known as 'hapua' (Paterson et al., 2001, Measures et al., 2020). Typically, river mouth channels are steered parallel to the coastline in the direction of littoral drift (Paterson et al., 2001), leading to an offset between the main river channel and mouth (Hart, 2009). Akin to the San Bernard River mouth, the Waimakariri river mouth channel was silted shut and enhanced backwater flooding motivated a successful dredging effort in 1930 (Boyle & May, 2011). Major flood events have been observed to increase lagoon erosion and potentially breach the river mouth bar, providing the river with an outlet to the sea (Measures et al., 2020; Paterson et al., 2001). However, the proximity of the San Bernard to the Brazos River delta along with the bifurcation of it's channel by the GIWW provide both an excess of littoral sediments to accrete at the river mouth and an artifical pathway for San Bernard River flow. These unique circumstances have led to the San Bernard losing its connection with the sea entirely, contrary to the natural mechanisms by which a river mouth can "survive" in a wave dominated coast.

4.3 Influence of the GIWW on San Bernard River Flow

It has been well documented that the GIWW influences morphodynamic properties of features throughout the gulf coast. The GIWW has been known to carry sediment and interrupt flow from rivers it intersects, disrupting the typical conditions of the rivers (Swarzenski et al., 2003). Combined with the dynamics of the Brazos River and locks for barge traffic, flows in the study area are observed to be complex in both fair-weather and high-discharge conditions (Sanchez & Parchure, 2001).

We hypothesized that the artificial bifurcation created by the GIWW interrupts the San Bernard River flow, reducing river discharge as it flows toward the coast. In the natural world, bifurcation occurs as a result of the sediment transport and discharge characteristics of the main river channel. Deposition of sediments in a river channel leads to the construction of a bar which diverts flow until two distinct channels are present (Jerolmack & Swenson, 2007). Contrary to this natural process, the bifurcation of the San Bernard preceded the deposition of sediment at the river mouth. With the construction of the GIWW in the 1940's, sediment deposition at the river mouth became favorable (via sediments supplied by both the San Bernard and the Brazos Delta), completing the inverted sequence of bifurcation. This sequence was further complicated by the geometry of the GIWW, which served as the distributary channels of the San Bernard, as channels are dredged to a uniform depth (typically 12 ft) and width (125 ft) approximately every 18 months to facilitate barge traffic. Under natural conditions distributary channels typically have lesser channel widths and depths than the parent channel (Jerolmack & Swenson, 2007). Once again the opposite is true of the GIWW, further complicating the flow and depositional properties of the intersection.

Here we provide a simple snapshot of the flow characteristics at the intersection of the San Bernard river and the GIWW. Results showed that the principal conduit for flow in the study area was the GIWW, with peak flow velocities greater than 35 cm/s, and flow was weakest on the abandoned limb of the San Bernard channel (Fig. 6). Flow down the GIWW was directed westward, away from the Brazos River. The west Brazos locks were open, potentially allowing the Brazos River to drive these flows. Fluxes increased downstream of the intersection with the San Bernard River, and a perturbation in the flow direction along the GIWW suggests that the San Bernard River interrupts and enhances its westward flow.

In both the upstream and downstream portions of the San Bernard river, flows were directed seaward, with considerable directional spread due to the wind field at the time of sampling. Wind stress played a role in these data as our vessel was pushed around as the wind blew. Furthermore, small wind-waves were seen during gusts. Flow velocities in the San Bernard were generally lesser than those of the GIWW and were more readily manipulated by the wind. Flow speeds in the upstream limb of the San Bernard were generally between 10 and 20 cm/s. In the downstream limb of the San Bernard River the flow was subdued relative to its upper limb, with speeds up to 12 cm/s (Fig. 5).

Mean water fluxes, calculated by taking the average of measured flow velocities multiplied by channel depth, further highlight that the GIWW is the main conduit for flow in the system. The mean water flux for the GIWW was approximately 0.66 m^2/s, while the upstream limb of the San Bernard had a mean water flux of approximately 0.39 m^2/s. In contrast, shallow depths (typically < 2 m) and relatively low flow velocities yielded a mean water flux of 0.15 m^2/s in the downstream limb of the San Bernard. Thus, San

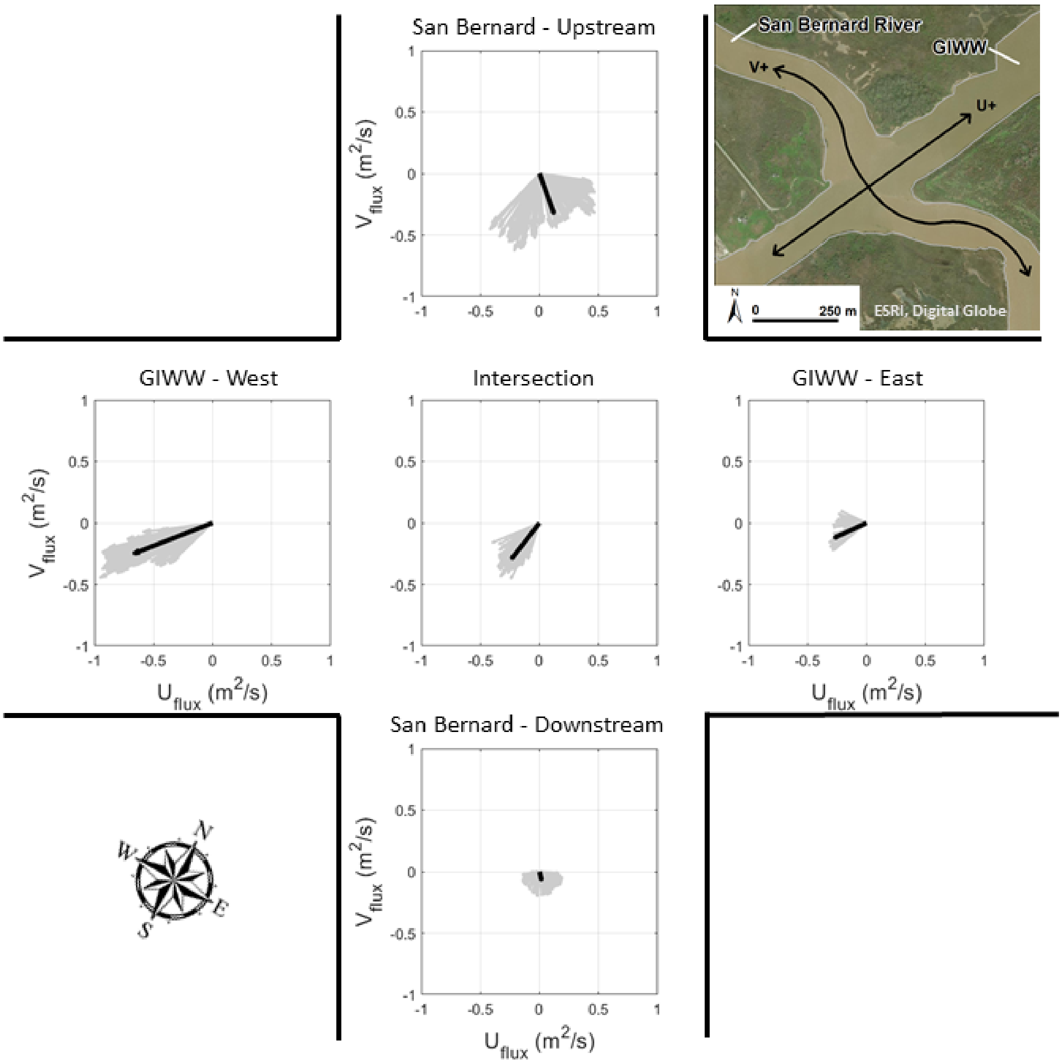

Figure 6. Observed directions and magnitudes of water flux at the intersection between the San Bernard and GIWW during calm-weather conditions show that the GIWW is the main conduit for flow of the system. San Bernard River contributes discharge to GIWW flow, leading to reduced velocities in the terminal limb of the channel downstream of the intersection. Mean water flux vectors shown in black, individual vectors shown in gray.

Bernard River flow appears to be captured more effectively by the GIWW rather than it's own downstream limb.

These results suggest that the San Bernard may play a tertiary role in the hydrodynamics of the area, behind the Brazos River and GIWW. In fair-weather conditions the San Bernard River system is controlled by coastal processes such as tides and flows from adjacent systems (the GIWW and Brazos River) rather than it's own discharge. Though the construction of the GIWW may have initially interrupted the flow of the San Bernard, the river now interrupts flow in the GIWW.

Figure 7. Series of aerial images that document the re-growth of the spit on the east flank of the San Bernard River mouth after being dredged open in 2009.

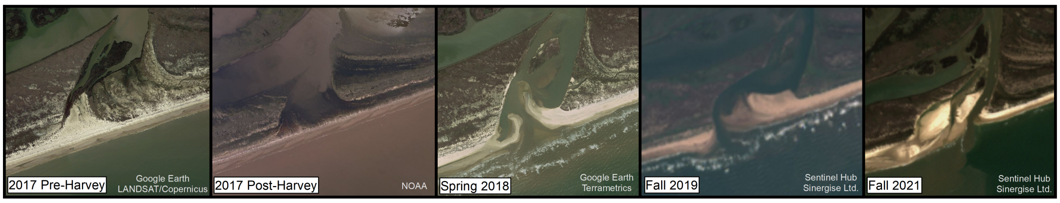

Figure 8. A series of aerial images show the brief breakthrough of the San Bernard River mouth after Hurricane Harvey flooding followed by formation of channel mouth bars and shallowing.

4.4 Futile Dredging of the San Bernard

A $2.4 million dredging project in 2010 removed 340,000 cubic yards of material from the San Bernard River mouth (Edwards, 2013), but within 4 years the cut was clogged once again. By 2011 beach sediments were reworked by wave action to form an elongated spit on the eastern flank of the artificial channel mouth. A series of amalgamated beach ridges began to form on the east side of the cut, narrowing and steering the channel clockwise until it was once again closed (Fig. 7). The dredged river mouth was closed by 2014 as a result of the same coastal processes that led to its initial closure in the late 1990's: a) accretion of a spit on the eastern flank by wave-driven transport of beach sediments, b) resultant steering of the San Bernard channel downdrift of it's dredged position, and c) tapering and closing of the river mouth. In 4-years the linked coastal rivers modified a man-made perturbation (the dredged channel) an order of magnitude faster than the previous response by the independent systems. This illustrates the control of wave-reworking of sediments on the river mouth in absence of a substantial flood event, such as a hurricane. Though the dredge provided short term benefits to the local ecology and GIWW currents (Edwards, 2013), a more substantial project must be implemented in order to permanently solve the problem.

4.5 Hurricane Harvey Impacts

In unengineered river systems an extreme storm is the primary mechanism to re-open a river mouth that is silted shut (Measures et al., 2020; Paterson et al., 2001). The landfall of Hurricane Harvey in late August of 2017 was a major flooding event that served as an extreme example of how the area responds to major flooding events. To better understand the dynamics of the area during these flooding episodes, aerial imagery and USACE bathymetric surveys taken shortly after Harvey help reveal what is happening to sediment and flow around the San Bernard. USGS gauge data reveals that the flooding experienced in the San Bernard created the highest stage ever recorded at that gauge, nearly 20 feet higher than the next closest flooding event. If the San Bernard was to ever gain enough erosive ability to cut through the sediment clogging its mouth, its strongest chance might have been during Hurricane Harvey.

Aerial images taken in the months after the hurricane reveal a brief breakthrough of the San Bernard River mouth due to the erosive ability of the floodwaters (Fig. 8). The flooding breached the ridges of the clogged river mouth at the location of the former natural and dredged channel mouths. The open channel has remained shallow and highly dynamic, with shoals and spits evolving on either side of the opening. A channel mouth bar on the eastern (updrift) flank of the river mouth had formed by December, and by March a similar bar formed on the western side. The nearly symmetrical bars are indicative of tidal reworking of beach sediments (Kraus & Lin, 2002). By the fall of 2019, an elongated spit on the eastern flank of the mouth has begun to steer the San Bernard channel to the southwest, tapering and closing the channel once again. The breach displayed geomorphic behavior similar to the life cycle of a tidal inlet, where spits on either side of the mouth waxed and waned according to littoral transport dynamics (Seminack & McBride, 2018). Orescanin et al., (2021) found that the dynamics of bar-built estuaries are controlled by the relationship between fluvial discharge and wave-driven alongshore transport of sediments. In the case of the San Bernard, the river mouth appears to be controlled by coastal processes (alongshore transport and tidal flushing) rather than fluvial discharge, thus leading to the closure of the river mouth.

4.6 Sedimentation of the Abandoned San Bernard Channel

The inactive San Bernard channel has remained relatively untouched by human activity, showing a buildup of sediment behind the clogged river mouth presumably due to reduced flow velocity at the intersection with the GIWW. Using USACE bathymetric surveys taken in June 2014 and April 2015, 10 months' worth of sedimentation are shown, typically between 20 and 50 cm with a maximum of 1 m. Depth values from both surveys were taken every 166 feet (50 m) from a 3500 foot (1066 m) transect running along the centerline of the inactive channel as defined by the USACE and plotted against each other (Fig. 8). Values spanning the width of the channel at interval were averaged and plotted, while the range of these values is shown in the bars. Rapid sedimentation in the inactive channel of the San Bernard is likely indicative of a reduction in water flux downstream of the intersection with the GIWW. Abrupt shallowing of the San Bernard channel downstream of the intersection may further divert river flow down the GIWW rather than towards the sea, promoting further deposition of sediments in the abandoned channel. Thus, the filling of the abandoned limb has likely worked in tandem with the accretion of beach sediments on the seaward side of the river mouth to reduce the probability of the San Bernard naturally reconnecting with the sea. Typically the shallowing and narrowing process continues as suspended sediments are deposited and erosion of the cut-bank is inhibited until the channel is completely filled (Toonen et al., 2012; Piegay et al., 2008). However, the San Bernard experiences massive flooding events such as Hurricane Harvey which may slow or eliminate this expected narrowing via erosion on the outer bank of the abandoned channel.

5 Discussion

5.1 Fate of the San Bernard

If the discharge and sediment of the San Bernard is not reaching the sea, it must be going somewhere else. Our results show that the GIWW may be the principal conduit for San Bernard River discharge rather than the terminal stem of its own channel. This suggests that the flow and sediment of the river is diverted into the canal rather than down its natural channel which allows the Brazos delta sediment to overpower and clog the mouth of the San Bernard. Documentation from numerous Texas government agencies also reveal flow travelling in the opposite direction in the northeast leg of the

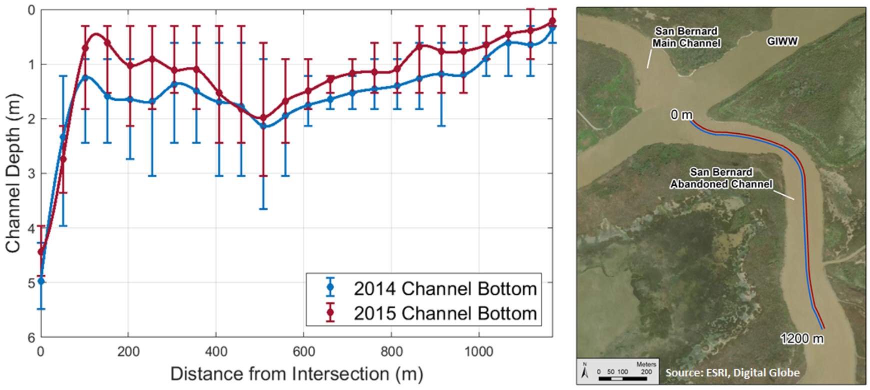

Figure 9. Bathymetric transects of the terminal limb of the San Bernard River in 2014 and 2015 show rapid accumulation of sediments throughout, suggesting reduced riverine flow promoting sediment deposition.

GIWW towards the west Brazos locks. These snapshots of the flow properties of the San Bernard could indicate that the GIWW acts as a 'T' shaped intersection, allowing runoff to travel in either direction along the GIWW rather than towards the sea.

If the San Bernard is ever to be restored to its natural state, ambitious and costly engineering projects are required. The two forces working against the San Bernard, flow down the GIWW instead of the main channel and Brazos sediment shoaling at the river mouth, must be addressed. As shown by the quick failure of the 2009 San Bernard dredging project, the longshore processes that transport Brazos sediment towards the mouth must be blocked by engineered structures or frequent maintenance dredging must be done in order to keep the mouth open. However, the diversion of flow at the intersection with the GIWW will continue to reduce flow volume and velocity down the terminal stretch of the San Bernard, leading to continued sedimentation.

Since 2018, governing institutions associated with the San Bernard have been working toward achieving a long-term solution, garnering strong public support. Beginning in July 2021 and completed in the spring of 2022, the "Mouth of the San Bernard River Restoration Project" was intended to permanently widen and deepen the San Bernard River mouth channel, enhancing the river's connection to the Gulf of Mexico. Material dredged in the abandoned channel was be used to replenish marsh habitat in the San Bernard Wildlife Refuge nearby (NOAA, 2021). Immediate benefits could include the reduction in flood hazard created by the backwater effect of the silted river mouth, calming of currents in the GIWW inhibiting barge traffic, and reduced sedimentation in the GIWW. Sediment buildup at the river mouth can be expected to continue as the long and shallow channel continues to display the tendency to close (Kraus & Lin, 2002).

This proposed project was more substantial and suggested a dredge that created a channel of 100 foot width and 10 foot depth stretching 1,800 feet into the Gulf of Mexico, requiring removal of 400,000 cubic yards of sand. In contrast to the dredging efforts of 2009, maintenance dredging will be performed every 3 – 5 years by the Port of Freeport to keep the river mouth free from excess sediment. Despite acknowledging continued sedimentation expected with this plan of action, the governing bodies have decided to move forward with the plan. Total cost estimates hover near $10 million, with federal grant money being the source of funding. The Port of Freeport, Phillips 66, and Brazoria County have agreed to split the cost of maintenance dredging, which is estimated to cost $2 million every few years (NOAA, 2021). Perhaps this recent push for the opening of the San Bernard will successfully alleviate the problems that have been persistent in the area for decades, but the longevity of this effort may not be cost effective. In fact, by October 2022 sedimentation has already made the outlet impassable to boat traffic as a result of low discharge over the previous summer (Holle, 2022). This highlights the necessity of consistent maintenance dredging, and shows that a "rigid coastline" approach is inherently at odds with the linked-coastal system.

6 Conclusion

Despite initial economic benefits of modifying coastal river channels, the difference in timescales between hydrodynamic perturbations and geomorphic responses can result in decades-delayed hazards. In this study we provide an example of two coastal engineering projects that modified the coastal reaches of nearby rivers, leading to a delayed and unintended linkage of the two systems that proved costly and hazardous. The first project, completed in 1929, was the diversion of the Brazos river to create the Port of Freeport, Texas, and the second was the construction of the GIWW in 1941 to facilitate barge traffic, bisecting the San Bernard river at its terminal limb. Though these projects were significant additions to economic activity to the state of Texas and beyond, the decades-delayed geomorphic response of the system to these perturbations illustrates the need for long-term, regional thinking when making channel modifications near the coast.

We conducted a simple evaluation of the morphodynamic factors leading to the closure of the mouth of the San Bernard River. The closure of the natural pathway of the San Bernard River has had negative effects on barge traffic, march ecology, and flooding hazards. A unique combination of coastal engineering projects, the diversion of the Brazos River channel and the construction of the GIWW, led to the San Bernard River mouth being clogged with sediments and shutting off its connection with the Gulf of Mexico. By diverting the Brazos River channel 10 km closer to the San Bernard River in 1929, engineers facilitated the rapid growth of a new river delta which encroached on and clogged the San Bernard via wave-induced alongshore transport of delta sediments. Furthermore, the construction of the GIWW diverted San Bernard River flow down the canal rather than towards the sea, leading to reduced fluvial discharge at the river mouth. This elevated the relative importance of coastal processes (alongshore transport and tidal flushing) in controlling the morphology of the river mouth.

Thus, the San Bernard River plays a peripheral role in the morphodynamics of the river mouth. As a result of reduced fluvial discharge, the river mouth behaves more like an inlet of a bar-built estuary where tides, alongshore transport, and storms dictate the morphology of the system. Efforts to correct the closure of the river mouth by routine dredging operations are presently underway, but the long-term results are yet to be seen. The dynamics of this engineered river mouth shows the tendency of human engineering projects to create unforeseen consequences as natural processes behave differently under these altered conditions.

7 Data Availability

Data files are publicly available and stored digitally at the Texas Data Repository (doi:10.18738/T8/INCGRW). The files include the Matlab processing script for processing and plotting Figure 6, a snapshot of water fluxes in an intersection-adjusted coordinate system, along with the raw source data collected from surfboard mounted ADCP profiler.

8 Acknowledgements

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9 References

Ashton, A. D., Giosan, L. (2011). Wave-angle control of delta evolution. *Geophysical Research Letters*, 38(13), 1–6. https://doi.org/10.1029/2011GL047630

Blake, E. S., Zelinsky, D. A. (2017). National Hurricane Center Tropical Cycle Report: Hurricane Harvey. 2005, 1–77. https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf

Barnard, P. L., Revell, D. L., Hoover, D., Warrick, J., Brocatus, J., Draut, A. E., ... Ryan, H. F. (2009). Coastal processes study of Santa Barbara and Ventura counties, California. *US Geological Survey Open-File Report*, 1029, 926.

Boyle, T. (2011). An investigation into the southward migration of the Waimakariri River mouth. *Environment Canterbury.*

Carlin, J. A., Dellapenna, T. M. (2014). Event-driven deltaic sedimentation on a low-gradient, low-energy shelf: The Brazos River subaqueous delta, northwestern Gulf of Mexico. *Marine Geology*, 353, 21–30. https://doi.org/10.1016/j.margeo.2014.03.017

Callahan, E. (2016, February 5). Support flows in for San Bernard. *The Facts* https://thefacts.com/news/article_5a6295a2-422d-510d-a3af-68bf3f1e95a4.html

Davis, R. A., Elko, N., Wang, P. (2018). Managing the Gulf Coast Using Geology and Engineering. *Geological Society of America.*

Edwards, R. (2013, May 19). The San Bernard River Mouth – One Year After Opening. *Friends of the San Bernard.*

Flatley, A., Rutherfurd, I. D., Hardie, R. (2018). River channel relocation: Problems and prospects. *Water*, 10(10), 1360.

Fraticelli, C. M. (2006). Climate forcing in a wave-dominated delta: The effects of drought-flood cycles on delta progradation. *Journal of Sedimentary Research*, 76(9–10), 1067–1076. https://doi.org/10.2110/jsr.2006.097

Hamilton, P. B., Lin, L., Jones, S. W. (2021). Investigation for Shoaling Reduction Along the Gulf Intracoastal Waterway (GIWW) at Caney Creek, Sargent, Texas. *Engineer Research and Development Center (US).*

Hart, D. E. (2009). Morphodynamics of non-estuarine rivermouth lagoons on high-energy coasts. *Journal of Coastal Research*, SPEC. ISSUE 56, 1355–1359.

Holle, K. (2022). Silt happens: Drought already causing a return of San Bernard build-up. *The Facts* `https://www.sanbernardriver.com/news_details.php?view=article&ref=archive&month=2&year=2016&id=773`

Jerolmack, D. J., Swenson, J. B. (2007). Scaling relationships and evolution of distributary networks on wave-influenced deltas. *Geophysical Research Letters*, 34(23), 1–5. `https://doi.org/10.1029/2007GL031823`

Kraus, N. C., Lin, L. H. (2002). Coastal Processes Study of San Bernard River Mouth, Texas: Stability and Maintenance of Mouth (Vol. 2). US Army Corps of Engineers, Engineer Research and Development Center, *Coastal and Hydraulics Laboratory.*

Measures, R. J., Hart, D. E., Cochrane, T. A., Hicks, D. M. (2020). Processes controlling river-mouth lagoon dynamics on high-energy mixed sand and gravel coasts. *Marine Geology*, 420(April 2019), 106082. `https://doi.org/10.1016/j.margeo.2019.106082`

National Oceanic & Atmospheric Administration (2021). Mouth of the San Bernard River Restoration Project.

Ndour, A., Laïbi, R. A., Sadio, M., Degbe, C. G., Diaw, A. T., Oyédé, L. M., ... Sambou, H. (2018). Management strategies for coastal erosion problems in West Africa: analysis, issues, and constraints drawn from the examples of Senegal and Benin. *Ocean Coastal Management*, 156, 92-106.

Nicholls, R. J., Wong, P. P., Burket, V. R., Codignotto, J., Hay, J. E., McLean, R. F., Ragoonaden, S., Woodroffe, C. D. (2007). Coastal systems and low-lying areas. *Climate Change 2007: Impacts, Adaptation and Vulnerability.*, 315–356.

Orescanin, M. M., Coughlin, J., Young, W. R. (2021). Morphological response of variable river discharge and wave forcing at a bar-built estuary. *Estuarine, Coastal and Shelf Science*, 258(May), 107438. `https://doi.org/10.1016/j.ecss.2021.107438`

Palmer, T. A., Montagna, P. A., Pollack, J. B., Kalke, R. D., DeYoe, H. R. (2011). The role of freshwater inflow in lagoons, rivers, and bays. *Hydrobiologia*, 667(1), 49–67. `https://doi.org/10.1007/s10750-011-0637-0`

Paterson, A., Hume, T., Healy, T., August, E., Paterson, A., Humej, T., Healyf, T. (2001). River Mouth Morphodynamics on a Mixed Sand-Gravel Coast Symposium (2000), *CHALLENGES FOR THE 21ST CENTURY IN COASTAL SCIENCES , River Mouth Morphodynamics on a Mixed Sand-Gravel Coast.* 34, 288–294.

Piégay, H., Hupp, C. R., Citterio, A., Dufour, S., Moulin, B., Walling, D. E. (2008). Spatial and temporal variability in sedimentation rates associated with cutoff channel in-fill deposits: Ain River, France. *Water Resources Research*, 44(5), 1–18. https://doi.org/10.1029/2006WR005260

Reguero, B. G., Bresch, D. N., Beck, M., Calil, J., Meliane, I. (2014). Coastal risks, nature-based defenses and the economics of adaptation: An application in the Gulf of Mexico, USA. *Coastal Engineering Proceedings*, 1(34), 25.

Rodriguez, A. B., Hamilton, M. D., Anderson, J. B. (2000). Facies and evolution of the modern brazos delta, texas: Wave versus flood influence. *Journal of Sedimentary Research*, 70(2), 283–295. https://doi.org/10.1306/2DC40911-0E47-11D7-8643000102C1865D

Roelvink, J. A. (2006). Coastal morphodynamic evolution techniques. *Coastal engineering*, 53(2-3), 277-287.

Seminack, C. T., McBride, R. A. (2018). A life-cycle model for wave-dominated tidal inlets along passive margin coasts of North America. *Geomorphology*, 304, 141–158. https://doi.org/10.1016/j.geomorph.2017.12.038

Stewart, Richard. (2009, January 18). Workers will dredge new mouth for San Bernard River. *Houston Chronicle*, 1–5.

Swarzenski, C. M. (2003). Surface-water hydrology of the Gulf Intracoastal Waterway in south-central Louisiana, 1996-99 (p. 51). *US Department of the Interior, US Geological Survey.*

Texas Department of Transportation. (2006). Gulf Intracoastal Waterway. *2005-2006 Legislative Report.*

Toonen, W. H., Kleinhans, M. G., Cohen, K. M. (2012). Sedimentary architecture of abandoned channel fills. *Earth surface processes and landforms*, 37(4), 459-472. https://doi.org/10.1002/esp.3189

Wang, B., Smith, L.C., Kyzivat, E.D., Fayne, J.V., Gleason, C.J., Langhorst, T., Harlan, M., Feng, D., Muñoz, S., Eidam, E. & Pavelsky, T. (2022, December). Tracking an ongoing river avulsion with satellite remote sensing and field measurements. *In Fall Meeting 2022. AGU.*

Wolfe, W. (2021, June 8). River Mouth Contract in Place San Bernard dredging could start in July. *The Facts Brazoria County.*