Nourishing an erosion hotspot

B.C. Ludka\textsuperscript{1}, A.P. Young\textsuperscript{1}, R.T. Guza\textsuperscript{1}, W.C. O’Reilly\textsuperscript{1}, M.A. Merrifield\textsuperscript{1}

\textsuperscript{1}University of California San Diego, Scripps Institution of Oceanography, La Jolla, CA 92093, USA

Key Points:

• The subaerial influence of relatively coarse beach nourishment sand is confined to 4\textsuperscript{4}km of coast, between a river mouth and groynes.
• Accretion and erosion hotspots are persistent, before and after nourishment.
• Patterns in the divergence of the drift, controlled by an ebb shoal, cause the hotspots.

Corresponding author: B.C. Ludka, bludka@ucsd.edu
Abstract
We describe the evolution of a moderately-sized (344,000 m$^3$), relatively coarse-grained beach nourishment, placed in 2012 in front of flood-prone homes at Imperial Beach, California. The subaerial sand spread laterally over a ~4 km span between groynes and a river mouth. By 2018, winter subaerial sand volumes in front of the flood-prone homes were eroded to near pre-nourishment levels, while sand accumulated near the river mouth. The observed alongshore patterns of nourishment erosion/accretion are consistent with the modeled convergence/divergence of alongshore currents driven by wave radiation stress $S_{xy}$ gradients associated with refraction over an ebb shoal. The same alongshore patterns of subaerial erosion/accretion were observed in the 6 years preceding the nourishment, indicating a wave-driven, erosion hotspot in front of the flood-prone homes, and an accretion hotspot on the north river bank. Persistent patterns of $S_{xy}$ gradients characterize wave-driven alongshore sand transport and provides a framework to inform sand management.

Plain Language Summary

Beach nourishment, the mechanical placing of sand, is widely used as shoreline protection. Predicting the evolution of nourishment sand levels remains challenging. Here we show that 7 yrs after placement, the influence of the relatively coarse-grained nourishment sand at Imperial Beach was largely confined to a ~4 alongshore span between a river mouth and groynes (e.g. stub jetties). Much of the sand placed in front of the flood-prone homes was transported alongcoast by waves to the edge of a river mouth. The dominant alongcoast evolution patterns of the beach could be predicted by multi-year sand level trends and estimated mean alongshore current gradient patterns observed prior to sand placement, and are controlled by the presence of an underwater topographic bump offshore. Our approach characterizes wave-driven alongshore sand transport patterns and provides a framework to inform sand management.

1 Introduction

Beach nourishment, the mechanical delivery of off-site sand to the subaerial beach, is used widely to provide oceanfront recreational space and protection from flooding and erosion (Clayton, 1991; Trembanis & Pilkey, 1998; Valverde et al., 1999; Hanson et al., 2002; Cooke et al., 2012; Luo et al., 2016; Palalane et al., 2016). Changes in basin-wide drainage, river damming, seawalls, and flood control have reduced natural sand supplies to the coast (Willis & Griggs, 2003; Young & Ashford, 2006; Young et al., 2010). Rising sea levels are increasing demands for beach nourishment (Fatorić & Chelleri, 2012; Hinkel et al., 2013), especially at chronic erosion hotspots (Stronkhorst et al., 2018). Understanding nourishment sand redistribution by waves and currents is crucial for designing effective nourishments (de Schipper et al., 2020).

Predicting beach nourishment evolution is challenging. Models must aggregate processes over a wide range of time-space scales using extensive parameterization, and site-specific calibration is required (Ruessink, 2005, 2006, 2008; Le Cozannet et al., 2019; Kroon et al., 2020). Although a site-calibrated model has skill at recreating the evolution of an unusually large mega-nourishment (Luijendijk et al., 2017), the task becomes more daunting when the nourishment volume is comparable to natural storm and seasonal sand volume fluctuations, which are themselves difficult to predict (Ludka et al., 2015; Kalligeris et al., 2020).

Nourishment evolution is further complicated by engineered hard structures and natural coastline features (e.g. river inlets, headlands) that can partially trap the alongcoast flow of sand (Bruun, 1995). Wave refraction over an ebb shoal can reverse the dominant alongshore sand drift resulting in adjacent erosion and accretion hotspots (Lowry...
& Carter, 1981; Stauble & Kraus, 1993); where the accretion hotspot abuts the inlet opening and forms a sand spit that can close the river mouth (Hayes et al., 1970; Komar, 1996; Hanes et al., 2011). Furthermore, coastline curvature near an inlet controls the tidal asymmetry of nearshore currents, and can dictate sediment transport patterns (Hopkins et al., 2017).

We investigate the alongshore evolution of a moderate-sized nourishment placed on an erosion hotspot surrounded by a complex coastline. In September 2012, Imperial Beach, the southernmost coastal community in California (Figure 1a), received 344,000 m$^3$ of relatively coarse grained sand ($D_{50} = 0.53$ mm nourished atop 0.25 mm native). The nourishment was placed in front of low-lying homes on Seacoast Drive prone to erosion and flooding (Figure 1b, c)(Gallien, 2016; Fiedler et al., 2020).

Two groynes (100150 m long stub jetties) are located north of the placement area (Figure 1b), and the Tijuana River mouth is to the south (Figure 1d). As of 2017, ~4.5 yrs after placement, ~half of the nourishment remained in the subaerial region between the river mouth and groynes, despite energetic El Niño waves (Ludka et al., 2016, 2018). Furthermore, the center of mass of subaerial sand between the river mouth and groynes shifted seasonally, in the direction of the seasonal mean alongshore current, with an overall southward trend towards the river mouth. In March 2016, ~3.5 years after nourishment placement, the Tijuana River mouth closed for the first time since 1984 (Goodwin, 1996; Zedler et al., 1992), causing hypoxic conditions in the estuary, killing leopard sharks (Figure 1d,e) and other biota (Baker, 2016). Here, we show that the observed alongshore patterns of erosion in the original nourishment placement region, and near-river-mouth accretion, are consistent with the modeled convergence/divergence of alongshore currents driven by wave radiation stress gradients associated with refraction over the Tijuana river ebb shoal.

2 Methods

2.1 Waves

A linear spectral refraction wave model provides hourly estimates of significant wave height $H_s$, and the alongshore radiation stress $S_{xy}$, at shore perpendicular MOP (Monitoring and Prediction) transects spaced ~100m in the alongshore (O’Reilly et al., 2016; Ludka et al., 2019). Swell waves (0.04-0.08 Hz) are initialized with deep water buoys located seaward of the Channel Islands, and propagated shoreward over the complex bathymetry of the Southern California Bight. Sea waves generated by local winds (212.5s) are initialized with nearby nearshore buoys (~20m depth). Updating the model with more accurate bathymetry improves model skill at Imperial Beach compared with previous studies (O’Reilly et al., 2016). The longshore radiation stress $S_{xy}$ is integrated over sea-swell frequencies (0.04-0.50 Hz) and directions

$$S_{xy} = \int \int (C_q(f)/C(f))E(f,\theta)\sin(\theta)\cos(\theta)d\theta df$$

where $E(f,\theta)$ is the frequency-directional spectrum, $C_q$ and $C$ are group and phase velocities, and $\theta$ is the wave angle relative to shorenormal. $S_{xy}$ has been related to both mean wave-driven alongshore currents and mean alongshore sediment transport. Erosion and accretion correspond to different signs of alongshore gradients $dS_{xy}/dy$, the so-called divergence of the drift (e.g.Shore Protection Manual (1984), and many others).

Offshore and north of the river mouth, a cobble ebb shoal modifies the wave field (Figure 2). To investigate the influence of the shoal, model results on transects are output at 9m and 3m depths below Mean Sea Level (MSL). The computationally efficient model does not account for wave breaking dissipation or non-linear wave shoaling which become important at the 3m depth shallow water locations. However, the linearly re-
fracted alongshore patterns in $S_{xy}$ in 3m depth are illustrative of the continued influence of the shoal in very shallow water. Qualitative analysis suggests the forcing of mean alongshore currents by $S_{xy}$ gradients is usually stronger than forcing by gradients in wave setup and other terms in an alongshore momentum balance (Hanson, 1989; Apotsos et al., 2008). Wu et al. (2020) showed that the mean alongshore dye transport velocity (alongshore and cross-shore averaged) at Imperial Beach was well correlated ($R^2 = 0.63$) with $S_{xy}$ with near-zero intercept.

At each alongshore location, the hourly $H_s$ and $S_{xy}$ (Eq 1) are averaged over the 6 yrs before nourishment (1 January 2007 - 31 Dec 2013); a few months after nourishment are appended to include full years. Results are almost identical for 5 post-nourishment years (1 January 2013 - 31 Dec 2018). Time-averaged $S_{xy}$ estimates were then alongshore smoothed with a 800m moving average (patterns were similar using 500m and 1000m boxcar filters). The difference between adjacent smoothed $S_{xy}$ estimates divided by the 100m separation are used as a proxy for the mean alongshore sand transport gradients. Areas of flux convergence correspond to accretion, whereas divergence corresponds to erosion (green and pink, respectively in Figure 2a).

### 2.2 Sand levels

Three sand level datasets are analyzed (Supporting Information Figure 1). Most (161 of 189) surveys were collected by an all terrain vehicle equipped with a global navigation satellite system and inertial measurement unit (Ludka et al., 2019). Sixteen surveys were conducted with a truck-mounted mobile Light Detection and Ranging (LiDAR) system (Matsumoto & Young, 2018). Twelve airplane-mounted LiDAR surveys were performed using various systems (Yates et al., 2008; Doria et al., 2016; Reineman et al., 2009; Melville et al., 2016; Young et al., 2018). LiDAR point clouds are processed, filtered to extract the beach, and manually edited to remove noise.

For all surveys, median values (to reduce the effect of outliers) are calculated in $\sim 100m \times 5m$ (alongshore x cross-shore) bins, matching the LiDAR resolution to the less dense ATV surveys. The data is then smoothed and interpolated (objectively mapped (Bretherton et al., 1976)) using cross-shore smoothing scale $L_{\tilde{y}} = 15m$, alongshore smoothing scale $L_{\tilde{x}} = 2 MOP$ lines ($\sim 200m$), and Normalize Mean Square Error threshold NMSE < 0.2 (following Ludka et al. (2019)). Eighteen of the 161 ATV surveys (magenta in Supporting Information Figure 1) had sections with unusually large alongshore transect spacing ($\sim 400m$) and these gaps were interpolated using a larger alongshore smoothing scale ($L_{\tilde{y}} = 4 MOP$ lines ($\sim 400m$). The 4km domain between the groynes and river mouth analyzed in Ludka et al. (2016, 2018, 2019) is extended to 10km. To include airplane LiDAR surveys flown during suboptimal tides, a +1m (relative MSL) elevation threshold (rather than MSL as in (Ludka et al., 2016, 2018, 2019)) is used to estimate cross-shore integrated subaerial sand volumes in 100m alongshore sections (Figure 2). The estimated beach area and subaerial volumes are set to zero for the few observations (4%) where the entire cross-shore beach at a 100-m alongshore section is below +1m (e.g. gaps at $\sim 4km$ in Supporting Information Figure 1a).

Sand dynamics near the river mouth (orange Figure 2, left) are more variable than the surrounding coastline, and surveys near the mouth were analyzed with higher space resolution. The river mouth width is often smaller than the 100m-spaced ATV surveys, and many surveys did not resolve the sand spits bounding the meandering river mouth. Therefore, for the mouth area we exclusively used LiDAR surveys that captured the entire cross-shore extent of the sand spits adjacent to the river mouth (Supporting Information Figure 1). Spits above +1m (relative to MSL) are extracted, median-binned, and linearly interpolated into consistent 3x3m grids. The 3x3m grids are then cross-shore integrated, and the sand volume above +1m (relative to MSL) is estimated (as elsewhere)
in ~100 m alongshore sections. Volumes estimated using the scheme of (Ludka et al., 2018, 2019) are similar (Supporting Information).

3 Results

3.1 Relationship between waves and nourishment evolution

The subaerial nourishment influence is largely confined between the groynes and the river mouth as shown by $\Delta$, the difference between mean volumes 6 yrs before and 6 yrs after nourishment (accreted green areas in Figure 3, left). The erosive pink band between locations C and D (Figure 3, left) is associated with river mouth migration (discussed below). Sand volumes south of the river mouth and north of the groynes show relatively little mean change before and after nourishment (Figure 3a,d).

In front of Cortez Avenue (Figure 3b) and Seacoast Drive, sand volumes increased after nourishment and then decreased, with winter sand volumes nearing pre-nourishment levels ~6.5 yrs after placement (winter 2019). Sand volumes north of the river mouth gradually increased after nourishment (Figure 3c). The estimated time-mean alongshore radiation stress gradient (and inferred wave-driven circulation) patterns in 3m depth (Figure 4c) are qualitatively consistent with patterns in the sand volume trends after nourishment (Figure 4b). Alongshore currents are predicted to converge (expected accretion, green) on the north side of the river mouth and diverge (expected erosion, pink) in front of Seacoast Drive.

The volume trends before and after nourishment have similarities and differences (Figure 4a,b). Patterns are similar in that an erosion hotspot (pink, location B) is located in front of flood-prone Seacoast Drive, with weak accretion (light green) just south of the groynes. Change magnitudes are larger after nourishment, owing to the increased amount of available sand at the nourishment. Accretion north of the river mouth (south of location C) is pronounced both before and after, although the location of maximum accretion shifts southward after nourishment.

The circulation inferred near the shoal is similar to previous studies (Hayes et al., 1970; Komar, 1996; Hanes et al., 2011); converging currents are offset slightly alongcoast (in this case northward) of the river mouth (location C Figure 4c) with diverging currents farther (north) away from the inlet (location B, Figure 4c). Changing the wave model output depth from 9 to 3m increases both $S_{xy}$ gradients and $H_s$ (Fig 2b,c), and shifts patterns slightly alongshore. Significant wave heights are larger at Seacoast Drive than further north in Imperial Beach (Figure 2c), which likely exacerbates Seacoast flooding problems (Fiedler et al., 2020). The largest waves are just north of the river mouth, near the historically (circa 1940-1960s) renowned Tijuana Sloughs big wave surf spot (Dedina, 2011).

3.2 River mouth migration

The river mouth (magenta squares in Figure 5a) was located using LiDAR surveys that captured both edges of the north and south river mouth bank, and satellite imagery (Landsat 7-8, Google Earth). $S_{xy}$ in 3m depth, alongshore averaged between the river mouth and groynes, oscillates seasonally but is southward on average (Figure 5c), consistent with the overall southward river mouth drift (Figure 5b). The southward wave forcing and mouth drift slowed slightly after nourishment (red and blue dashed in Figure 5a,b). Mouth location oscillated more dramatically in the post-nourishment period, with a swift southward migration in 2015/16 perhaps in response to strong southward alongshore currents induced by El Niño storm waves (Ludka et al., 2018). Overall, seasonal variations in the directional quadrant of incident waves, apparent in the smoothed
(3 month moving average) alongshore averaged (between the river mouth and groynes) $S_{xy}$, are uncorrelated with fluctuations in mouth location.

In March 2016 (brown vertical line Figure 5b) the river mouth closed for the first time since 1984 (Goodwin, 1996; Zedler et al., 1992). The southward wave forcing (Figure 5c), coupled with six years of nourishment sand accumulation on the north side of the river mouth (Figure 3c) may have contributed to the 2016 closure. Factors including estuary channel migration and changes in river flow and tidal prism may also be important. The 1984 closure followed a strong, wet 1983 El Niño winter with dune breaching and filling of estuary channels that did not occur in the dry El Niño prior to the 2016 closing. Other estuary mouths in the region are constrained by jetties on at least one lateral boundary, and close more frequently than the Tijuana River, including during El Niño winters (Safran et al., 2017; Harvey et al., 2020; Young et al., 2018). During 2017-2019, the (mechanically reopened) mouth again drifted south.

4 Summary and Discussion

The subaerial influence of relatively coarse-grained sand placed at Imperial Beach is largely confined to a ~4km stretch of coast, between a river mouth and groynes. An ebb shoal creates gradients in the alongcoast divergence of the drift, as evidenced by erosion and accretion hotspots in the multi-year sand level trends and estimated alongshore radiation stress gradient patterns. The influence of nourishments on river inlet migration and closure is unclear. A substantial amount of nourishment sand was transported to the north side of the river mouth prior to the rapid southward mouth migration and closure during the 2016 El Niño.

Imperial Beach was nourished in 2001 and 2012, with volumes of 97,000 and 344,000m$^3$ respectively. Six years after the most recent coarser-grained placement, the winter beach at the placement site in front of flood prone low-lying homes is nearing pre-nourishment levels (Figure 3b). The 2012 nourishment was constructed with coarser sand ($D_{50} = 0.53$) than the 2001 nourishment ($D_{50} = 0.38$) to increase subaerial sand retention, but sand similar to native ($D_{50} = 0.25$) is often preferred to minimize negative ecological impacts (Speybroek et al., 2006).

The City of Imperial Beach Sea Level Rise Assessment (Revell Coastal, 2016) considers coastal adaptation techniques including: 1) additional nourishment 2) building additional groynes combined with more nourishment and 3) managed retreat (i.e. landward redevelopment). A substantial fraction of the 2012 Seacoast nourishment remained subaerial in 2019, but was spread both northward and (especially) southward. The 5-7 yr observed lifetime in front of Seacoast Drive, for this moderately-sized relatively coarse-grained nourishment, of course depends on wave conditions and sediment size. Research is needed to determine if increased river mouth closures and inlet dredging will be required with additional nourishment, and to alert managers (Collins, 2018). Sand dredged from near the river mouth could potentially be recycled for nourishment placement in front of Seacoast Drive. Additional groynes might trap relatively coarse-grained nourishments alongcoast, while sand volumes downdrift could decrease. The effectiveness and impacts of groynes are not well understood (Galgano Jr, 2004). If the infrastructure on the coastline (e.g. riprap fronting Seacoast Drive) is not repaired after future storm damage, or is removed, the coastline shape could change. Changing coastline shape can strongly influence nearshore currents and sand transport near inlets (Hopkins et al., 2017). Sand distribution is typically one of many factors (e.g. groundwater (Hargrove, 2015), recreational (Whitlock, 2012; County, 2013), and ecological impacts (Wooldridge et al., 2016)) considered in coastal management decisions (de Schipper et al., 2020). Our approach characterizes wave-driven alongshore sand transport patterns and provides a framework to inform sand management.
Acknowledgments

Funded by the California Department of Parks and Recreation, Natural Resources Division Oceanography Program (C19E0026) and the U.S. Army Corps of Engineers (W912HZ192). Field equipment was capably maintained and operated by B. Boyd, M. Burgess, G. Boyd, R. Grenzeback, L. Parry, K. Smith, and B. Woodward. M. Okihrio provided essential logistical support. Monica Almeida and Kellie Uyeda from the Tijuana River Estuarine Research Reserve extracted and provided the Tijuana river mouth locations from the satellite imagery. Jeff Crooks provided valuable insight into river mouth dynamics.

Data Availability

ATV data through 2016:


with corresponding additional documentation:

https://www.nature.com/articles/s41597-019-0167-6

El Niño (2015-16) airborne LiDAR flights:

https://library.ucsd.edu/dc/collection/bb80931629

Other airborne LiDAR flights:

https://coast.noaa.gov/digitalcoast/data/home.html

Landsat imagery:

https://gisgeography.com/usgs-earth-explorer-download-free-landsat-imagery/

Truck LiDAR and post-2017 ATV beach surveys, CDIP wave model output and model input bathymetry will be stored in a UCSD Library repository.
Figure 1. (a) Google Earth image of the study site. The City of Imperial Beach is bounded by San Diego Bay, Tijuana Estuary, and the Pacific Ocean. The beach nourishment placement site is outlined in red. (b) Aerial image of the region outlined in orange in (a) shows the in-progress Imperial Beach nourishment (red dots outline final placement). The nourishment was placed to increase beach recreation and tourism, and to protect low-lying homes on Seacoast Drive. Image courtesy of Eddie Kisfaludy and Wildcoast. (c) Wave overtopping on Cortez Avenue flooding into Seacoast Drive. The intersection of Cortez Avenue and Seacoast Drive is marked with a star in (b) and (c). (d) Aerial image of the Tijuana Estuary. Image courtesy of Ralph Lee Hopkins. (e) Dead leopard sharks, killed by hypoxic conditions in the Tijuana Estuary caused by river mouth closure. Image courtesy of Serge Dedina.
Figure 2. The influence of the ebb shoal. (Left) Bathymetry relative to MSL showing the cobble shoal offshore and north of the river mouth. The area of migrating sand spits surrounding the Tijuana river mouth (Figure 5a) is outlined in orange. The original nourishment placement region (outlined in red) fronts the low-lying portion of Seacoast Drive (bright blue bar). The modeled time-averaged (2007-2012), (a) alongshore smoothed $S_{xy}$ (alongshore radiation stress) (b) $dS_{xy}/dy$ (radiation stress gradient) and (c) significant wave height. The location of Seacoast Drive is highlighted in blue, while the area over which the river migrated is orange. The radiation stress gradient and significant wave height are also overlaid on the 9 and 3m depth contours of the map (see legends). Locations A,B,C,D are discussed below.
Figure 3. Alongshore extent of subaerial nourishment influence. (Left) Difference (Δ) of the time-mean subaerial (above 1m rel MSL) sand volume (6 yr average) before and (6 yr) after nourishment, at 100m-wide alongshore sections. The shift in the time series mean is large and positive (green) between the Tijuana River mouth and groynes, suggesting that this is the subaerial region most influenced by the nourishment. The original nourishment placement region is outlined in black. The area of migrating sand spits surrounding the Tijuana river mouth (Figure 5a) is outlined in orange. Subaerial sand volume time series (a-d) are shown for 100m alongshore sections A-D, respectively. The time-mean subaerial volume before(after) nourishment placement are solid red(blue) lines. Dashed lines are best fit trends.
Figure 4. Alongshore patterns (100m alongshore sections) of observed sand level change and modeled alongshore current gradients. (a) Pre-nourishment subaerial volume trends (e.g. red dashed lines in Fig 2a-d). (b) Post-nourishment subaerial volume trends (e.g. blue dashed lines in Fig 2a-d). Pink areas eroded and green areas accreted. (c) Alongshore gradient of the time-average alongshore smoothed $dS_{xy}/dy$ estimated in 3m depth; a proxy for the mean alongshore current and sand transport gradients both before and after nourishment. Pink (green) marks areas where currents diverge (converge). Locations B,C,D are shown in Figures 2 (left) and 3 (left). The original nourishment placement region (B) is outlined in black. The area of migrating sand spits surrounding the Tijuana river mouth (Figure 5a) is outlined in orange.
Figure 5. River mouth evolution. (a) Example LiDAR surveys (elevation rel. MSL) showing the evolution of the river mouth and adjacent sand spits. Center of river mouth is marked with magenta square. (b) River mouth location versus time. Location is distance along red line in (a) relative to March 2007. Large black squares denote location from LiDAR survey, while small gray circles are from satellite imagery. Vertical black line marks 2012 nourishment, while thinner brown vertical line marks river mouth closure a few days after the March 2016 survey. River mouth locations in (a) are marked with magenta box. Trends characterizing river mouth migration are shown before (red dashed) and after (blue dashed) nourishment. (c) $\langle \langle S_{xy} \rangle \rangle_{3m}$ versus time, where $\langle \langle S_{xy} \rangle \rangle_{3m}$ is 3-month moving average of the alongshore averaged (from the river mouth to groynes) radiation stress in 3m depth. Mean $\langle \langle S_{xy} \rangle \rangle_{3m}$ for pre- and post-nourishment periods are similar (-37 cm$^2$ and -31 cm$^2$, respectively, red/blue dashed lines in 5c).
References


mospheric and oceanic technology, 26(12), 2626–2641. doi: https://doi.org/10.1175/2009JTECHO703.1


Supporting Information: Nourishing an erosion hotspot

B.C. Ludka¹, A.P. Young¹, R.T. Guza¹, W.C. O’Reilly¹, M.A. Merrifield¹

¹University of California San Diego, Scripps Institution of Oceanography, La Jolla, CA 92093, USA

Sand levels

Three sand level datasets are analyzed. Most (161 of 189) surveys were collected by an all terrain vehicle equipped with a global navigation satellite system and inertial measurement unit (black dots, Figure S1) (Ludka et al., 2019). Sixteen surveys were conducted with a truck-mounted mobile Light Detection and Ranging (LiDAR) system (red dots, Figure S1) (Matsumoto & Young, 2018). Twelve airplane-mounted LiDAR surveys were performed using various systems (blue dots, Figure S1) (Yates et al., 2008; Doria et al., 2016; Reineman et al., 2009; Melville et al., 2016; Young et al., 2018). LiDAR point clouds are processed, filtered to extract the beach, and manually edited to remove noise.

For all surveys, median values (to reduce the effect of outliers) are calculated in ~100m x 5m (alongshore x cross-shore) bins, matching the LiDAR resolution to the less dense ATV surveys. The data is then smoothed and interpolated (objectively mapped (Bretherton et al., 1976)) using cross-shore smoothing scale \( L_x = 15 \) m, alongshore smoothing scale \( L_y = 2 \) MOP lines (~200m), and Normalize Mean Square Error threshold \( \text{NMSE} < 0.2 \) (following Ludka et al. (2019)). Eighteen of the 161 ATV surveys (magenta, Figure S1) had sections with unusually large alongshore transect spacing (~400m) and these gaps were interpolated using a larger alongshore smoothing scale \( L_y = 4 \) MOP lines (~400m).

To include airplane LiDAR surveys flown during suboptimal tides, a +1m (relative MSL) elevation threshold (rather than MSL as in (Ludka et al., 2016, 2018, 2019)) is used to estimate cross-shore integrated subaerial sand volumes in 100m alongshore sections. The estimated beach area and subaerial volumes are set to zero for the few observations (4%) where the entire cross-shore beach at a 100-m alongshore section is below +1m (e.g. gaps at ~4km in Figure S1).

Sand dynamics near the river mouth are more variable than the surrounding coastline, and surveys near the mouth were analyzed with higher space resolution. The river mouth width is often smaller than the 100m-spaced ATV surveys, and many surveys did not resolve the sand spits bounding the meandering river mouth. Therefore, for the mouth area we exclusively used LiDAR surveys that captured the entire cross-shore extent of the sand spits adjacent to the river mouth (Figure S1). Spits above +1m (relative to MSL) are extracted, median-binned, and linearly interpolated into consistent 3x3m grids. The 3x3m grids are then cross-shore integrated, and the sand volume above +1m (relative to MSL) is estimated (as elsewhere) in ~100m alongshore sections.

Comparing sand volume calculation methods

Ludka et al. (2019) estimated subaerial volumes using a static domain, bounded horizontally by the average location of the MSL contour and the backbeach, and from below by the minimum observed surface. Here we estimate subaerial volume with meandering boundaries as the amount of sand above +1m (relative to MSL) accounting for river mouth and sand spit migration, and accepting the suboptimal tides of some LiDAR surveys. Using the lower resolution static domain, most surveys with data near the river mouth (Figure S1a, dots in brown section) are included in the river mouth analysis. The

Corresponding author: B.C. Ludka, bludka@ucsd.edu
static domain sacrifices spatial completeness and resolution for temporal resolution. Results were similar using static and meandering boundaries. One difference (not shown) is that the initial erosion of the nourishment pad is more pronounced using the meandering domain, because the beach width based on the +1m contour shrinks drastically after nourishment.