Estuarine, Coastal and Shelf Science 212 (2018) 203–209

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Beach nourishment is not a sustainable strategy to mitigate climate change

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ABSTRACT

Some studies published over the past several decades have concluded nourishment of oceanic beaches is a viable strategy to mitigate climate change. However, these were generally too limited in scope to accurately evaluate beach nourishment because each omit one or more of the following: (1) a realistic assessment of potential borrow area sand volume, (2) native beach compatibility, (3) construction costs, (4) all vulnerable geomorphic elements of the coastal zone, and (5) environmental impacts. When all of these parameters are considered, the results are markedly different. To demonstrate our point, we evaluated the recommendations of Houston (2017) using all five parameters. Contrary to Houston, we provide multiple lines of evidence that beach fill projects are not a sustainable strategy to protect or defend oceanic beaches of the Florida panhandle (USA), nor likely most of the world's developed coastlines at risk to the effects of climate change. The nourishment of oceanic beaches as historically constructed will surely continue over the next several decades. But, it must be done as an interim strategy during the formulation and implementation of a robust, long-term adaptive management strategy that incorporates managed withdrawal from the coastline.

1. Introduction

The rate of global eustatic sea level has accelerated as a consequence of human-caused climate change, averaging about 2 mm yr^{-1} since 1900 and over 3 mm yr^{-1} since 1993 (Church and White, 2011). Relative to the year 2000, sea level is very likely to rise 30–130 cm by 2100 (Sweet et al., 2017). An increase in the number of intense tropical cyclones is also predicted as the climate warms (USGCRP, 2017). Both of these phenomena are already impacting the coastal zone, as evidenced by expanded nuisance flooding, submergence of low lying areas, increased erosion, wetland loss, and salt water intrusion into aquifers and rivers. Future climate change will exacerbate the frequency, duration, and extent of these phenomena (Bird, 1985; National Research Council, 1987; Nicholls et al., 2007; Nicholls and Cazenave, 2010).

Historically, a wide range of shore protection installations have been constructed to mitigate coastal erosion and flooding (climate change), including ‘hard’ (i.e., seawalls, groins, breakwaters, revetments) and ‘soft’ (i.e., dune construction, beach nourishment) structures (c.f. National Research Council, 1987). The currently preferred approach is beach filling (Peterson et al., 2006) or hereafter nourishment because hard structural solutions have been shown to have detrimental effects on adjacent beaches and coastal ecology (c.f. Cooke et al., 2012; Hamm et al., 2002). Also, the construction and maintenance costs of hard structures are much higher than nourishment (Hoffman, 2016; Leatherman, 1996).

A number of studies have been conducted to assess the viability of beach nourishment as a cost-effective, long-term management strategy to mitigate climate change. These typically include an assessment of potential offshore sand reserve volume (Leatherman, 1996; Titus et al., 1991) and an economic analysis to determine the extent and/or cost of requisite nourishment (Hinkel et al., 2013; Langedijk, 2008; National Research Council, 1995; Yoshida et al., 2014). While these studies should be considered an important first step, there exist several significant limitations to the scope of each. First, volume estimates of potential marine sand reserves are generally based upon limited (i.e., reconnaissance-level surveys) data, making it highly likely the volume of recoverable sand will be much less than initially calculated. Second, cost estimates are often based upon existing market conditions. Third, in no case was native beach compatibility considered, nor the full extent of associated environmental impacts.

This investigation was precipitated by the recent publication of Houston (2017), in which he states annual beach nourishment along more than three-hundred kilometers of Florida panhandle shoreline (Fig. 1) can offset the effects of a sea level rise of between 0.38 m and 0.68 m (Church et al., 2013) by the year 2100. However, like the global (Hinkel et al., 2013), hemispheric (Hamm et al., 2002), national (Leatherman, 1989; National Research Council, 1987; Yoshida et al., 2014), and regional (Langedijk, 2008) assessments that preceded Houston (2017), the analysis was too limited in scope to accurately evaluate beach nourishment as a viable mitigation strategy. A more realistic assessment should consider: (1) potential marine sand reserve volume, (2) native beach compatibility, (3) construction costs, (4) all vulnerable geomorphic elements of the coastal zone, and (5)

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https://doi.org/10.1016/j.ecss.2018.07.011
Received 5 February 2018; Received in revised form 25 June 2018; Accepted 7 July 2018

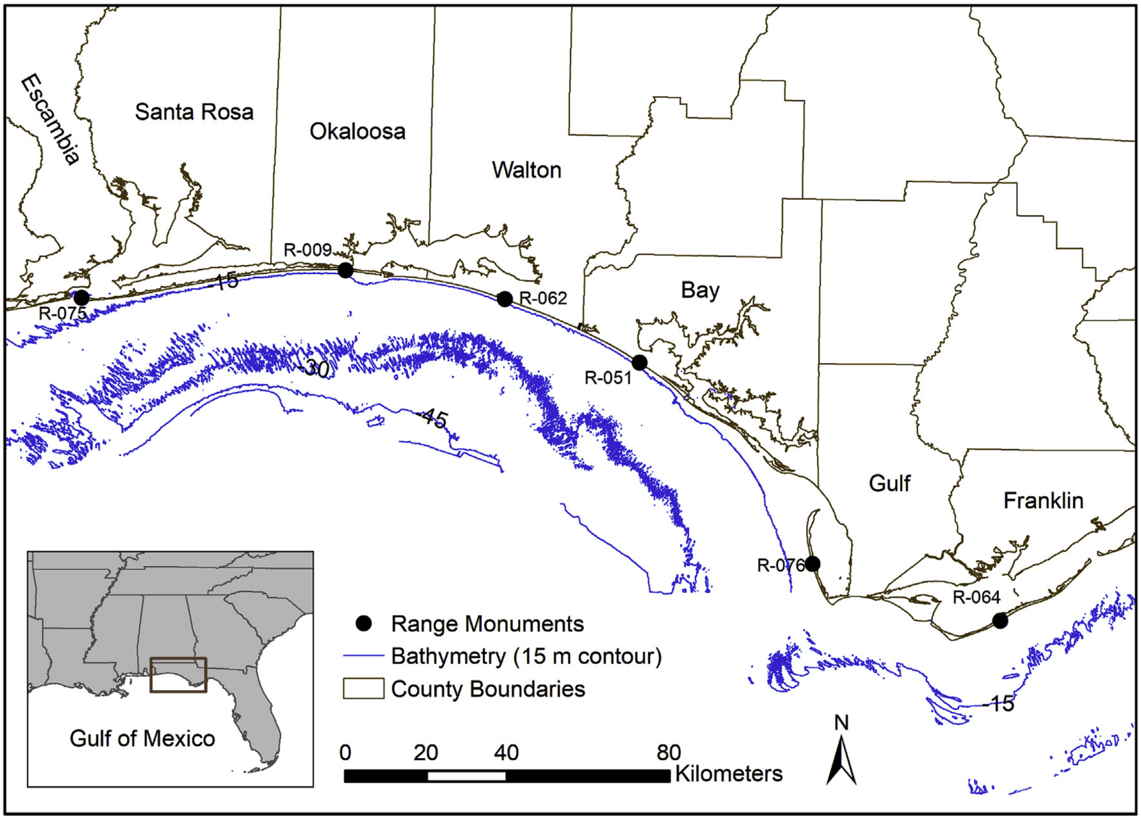

Fig. 1. Location of seven coastal counties of the Florida panhandle. Also shown are locations of six LIDAR-based topographic surveys shown in Fig. 5.

environmental impacts. When all of these parameters are considered, the results are markedly different. To demonstrate this point, the Florida panhandle study was evaluated using all of these parameters and the results clearly indicate beach nourishment is not a sustainable strategy to mitigate the effects of climate change along the Florida panhandle. Nor is beach nourishment likely a sustainable strategy to protect and defend most of the world's developed coastlines at risk to the effects of climate change.

2. Background

The coastal zone of the Florida panhandle is at high risk to climate change given its low elevation, erodible substrates, present and past evidence of shoreline retreat, and high probabilities of tropical storm and hurricane landfall (storms) (Gornitz et al., 1994). Based upon an analysis of coastal data collected since the 1800s, the annual placement of roughly 1.57 m^3 to 2.42 million m^3 (Table 1) of sand on 334 km of Gulf Coast oceanic shoreline is required to mitigate future impacts of sea level rise (Houston, 2017). Consideration of beach nourishment as a viable strategy to combat sea level rise is not new (c.f., Langedijk, 2008; Leatherman, 1989; Yoshida et al., 2014). In reality however, it is unlikely the requisite scale of construction could be sustained given what is known about compatible marine sand reserves and ballooning costs.

3. Marine sand reserve volume

Permitted borrow areas along the Florida panhandle are located proximal to the coastline (< 5 km), in relatively shallow water (< 15 m), are of limited horizontal scale (< 1 km), and typically contain less than 2 million cubic yards of sand (Fig. 2, Supplemental Table 2). Most of these have already been utilized or will be dredged in the next decade. Remaining permitted borrow areas are scant and will not meet the long-term volume requirements to sustain a nourishment campaign along the Florida panhandle to the end of this century.

By contrast, most *potential* sand reserves along the Florida panhandle are located more than 10 km offshore and in water depths

Table 1
Annual beach nourishment sand requirements proposed by Houston (2017) to maintain the Florida panhandle's 2016 shoreline position under four IPCC (Church et al., 2013) sea level rise scenarios until the end of this century. Also shown are estimated annual construction costs, held constant at \$30 m^{-3} and average annual State cost sharing to design and construct non-Federal planned beach nourishment projects. Appropriation data from Supplemental Table 1.

County	Average annual sand volume requirements (m^3x10^6)				Average annual cost ($\$x10^6$)				Average annual State appropriation FY 2013–2017 ($\$x10^6$)	
	RCP2.6	RCP4.5	RPC6.0	RCP8.5	RCP2.6	RCP4.5	RPC6.0	RCP8.5	Requested	Received
Escambia Santa Rosa	0.21	0.26	0.27	0.37	6.3	7.8	8.1	11.1	6.5	1.8
Okaloosa	0.08	0.10	0.10	0.14	2.4	3.0	3.0	4.2	0.0	0.0
Walton	0.80	0.90	0.90	1.20	24.0	27.0	27.0	36.0	0.0	0.0
Bay	0.13	0.15	0.16	0.19	3.9	4.5	4.8	5.7	0.9	0.9
Gulf	0.25	0.27	0.28	0.33	7.5	8.1	8.4	9.9	2.3	1.0
Franklin	0.10	0.13	0.13	0.19	3.0	3.9	3.9	5.7	0.0	0.0
Total	1.57	1.81	1.84	2.42	47.1	54.3	55.2	72.6	9.7	3.8

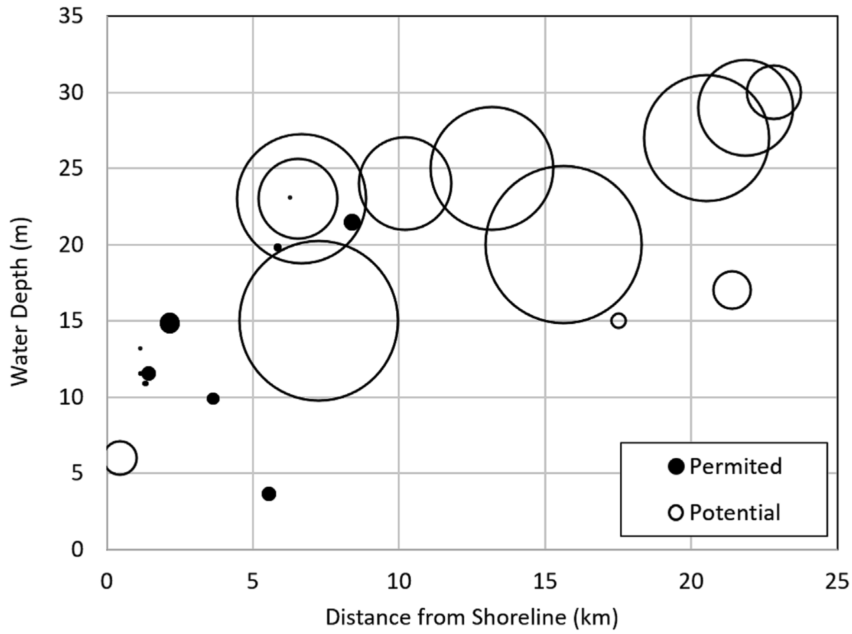

Fig. 2. Balloon scatter plot of permitted borrow area and potential sand reserve centroid distance to shoreline and relative sand volume (balloon diameter). Data from Supplemental Table 2.

exceeding 15 m (Fig. 2). Although identified primarily by limited, reconnaissance-level geophysical surveys, these areas could yield Houston's requisite sand volumes for all seven counties through the end of this century.

4. Marine sand reserve compatibility

According to Florida Law (Chapter 62B-41), the sand used for beach nourishment must be similar to the characteristics of native beach sediment. Defined as beach compatible fill, this material is mandated in an attempt to maintain the general character and function of Florida's native beaches. The principle characteristics used to assess compatibility are sediment texture (i.e., size, sorting), composition (i.e., percent carbonate), and color.

The native beaches of the Florida panhandle consist of fine-grained, well to moderately-well sorted, white sand (Fig. 3, Supplemental Table 3). Historically, the search for borrow areas containing compatible sand has been challenging because panhandle residents have demanded only bright, white sand be used to nourish their native beaches (c.f. Judnich, 2017). *Permitted* borrow areas have typically contained fine sand like the native beaches, but these deposits are often more poorly sorted and slightly darker (Fig. 3).

The sedimentology of *potential* sand reserves is based primarily upon a limited number of reconnaissance-level grab samples, but the data suggest they do not contain sand compatible with the native beaches as it is generally coarser, more poorly sorted, and often darker (Fig. 3). Should a subsequent and more detailed geotechnical survey of these areas reveal one, another, or all of the marine sand deposits are not compatible with native beaches, a discussion amongst stakeholders regarding the cost (i.e., loss of aesthetic and ecologic function) and benefits (i.e., protection of capital investment) of beach nourishment will surely follow. Compromises will likely be made to the scale of

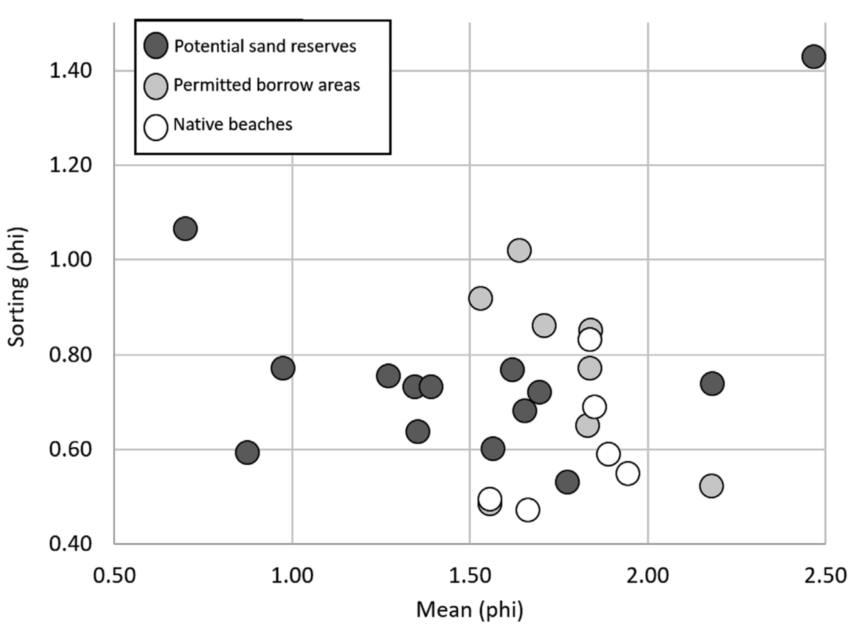

Fig. 3. Scatter plot of panhandle native beach, permitted borrow area, and potential sand reserve granularmetrics. Permitted borrow areas are more poorly sorted than native beaches. Potential sand reserves differ from native beaches in mean grain size and sorting. Series shading proportional to color of sand. Data from Supplemental Table 3.

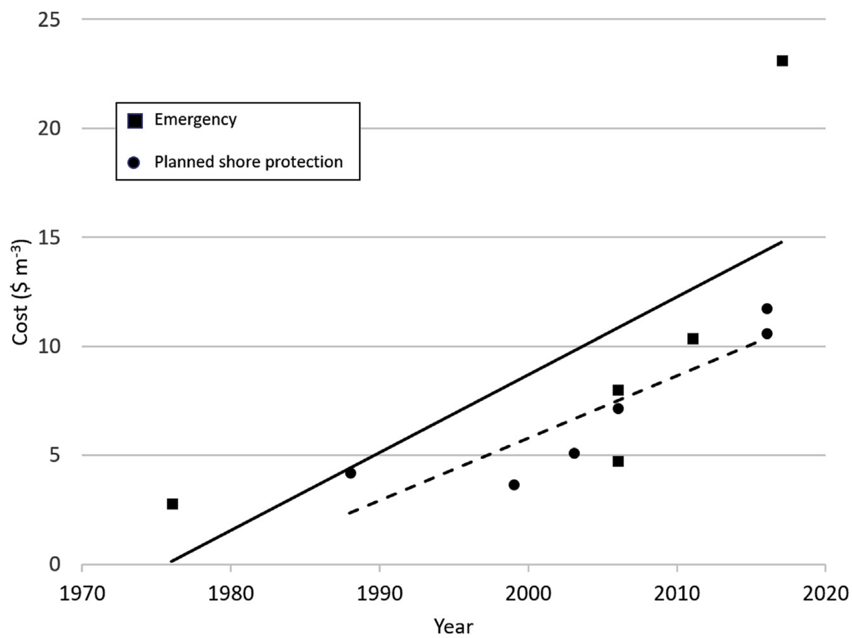

Fig. 4. The cost of historical beach nourishment as a function of construction year and project type. Linear fit trend lines for emergency (solid) and planned (dashed) projects indicate costs, as measured per cubic meter of emplaced sand, are rising about $5 every 15 years. Data from Supplemental Table 4.

panhandle nourishment required to mitigate climate change.

5. Construction costs

The cost to nourish beaches along the Florida panhandle has steadily risen from about $5 m^{-3} during the late twentieth century to more than $10 m^{-3} over the past decade (Fig. 4, Supplemental Table 4). Construction bids now often exceed a project's budget. For example, bids to nourish Gulf County's St. Joseph Peninsula were 150%–300% higher than expected (c.f. Croft, 2017). Prices ranged from $15 m^{-3} to $26 m^{-3}.

The projected annual cost to sustain an 84-year beach nourishment program along the Florida panhandle is shown in Table 1. Costs range between $47.1 and $72.6 million per year, depending upon the sea level rise scenario that ultimately materializes. For perspective, the average annual Federal expenditure on all shore protection projects constructed in the United States by the Army Corps of Engineers between 1950 and 1993 was only $17 million (National Research Council, 1995). Our estimates assume the cost per cubic yard of emplaced sand stays constant at $30 m^{-3} until the end of this century. They are therefore conservative given historical construction costs, as measured per cubic meter of emplaced sand, have been rising about $5 every 15 years (Fig. 4). At the current rate of rise, the cost of nourishment will exceed $30 m^{-3} by mid-century.

Between 2013 and 2017, the Florida legislature appropriated an average of $3.8 million in support of the State's comprehensive long-term beach management plan for the panhandle (Supplemental Table 1). Local cost sharing was generally between 100% and 200% of the State appropriation. Even if it is assumed panhandle counties will continue to receive about 20% of the State's annual appropriations and the local match could be sustained at 200% throughout this century, the sum is not enough to pay for the annual nourishment of the panhandle shoreline under even the lowest (RCP2.6) sea level rise scenario as proposed by Houston (2017).

To complicate matters, construction costs will surely rise as the search and recovery of sand moves further offshore (Fig. 2) and the requisite volume increases in response to a non-linear acceleration in the rate of sea level rise (Sweet et al., 2017) and increasing storminess (USGCRP, 2017), neither of which Houston (2017) factored into his analysis. It is thus highly probable annual construction costs to nourish panhandle beaches will quickly overwhelm existing local and state program budgets.

6. Coastal geomorphology

Coastal geomorphology (i.e., landform, topography) dictates the magnitude and extent of erosion and flooding caused by sea level rise and storms. As a case in point, the coastal geomorphology of the Florida panhandle was evaluated using photogrammetry and digital elevation models to identify areas at risk to erosion and flooding (see Supplemental Text DEM Methodology). In all seven counties, vulnerability was not limited to the oceanic shoreline (Fig. 5, Supplemental Table 5) and therefore their nourishment alone will not mitigate the effects of climate change. The protect and defend strategy of beach nourishment would have to be expanded to include all vulnerable shorelines (i.e., back barrier, mainland, embayment, riverine, tidal, lacustrine). The expansion of depression ponds on the barrier island would also have to be addressed, as would vulnerable low-lying infrastructure (i.e., roads, gravity driven sewer and storm water systems).

A more realistic assessment must address the risks associated with all vulnerable geomorphic elements of the landscape, which will undoubtedly require even more resources to design and construct.

7. Environmental impacts

Historically, the ecological and associated economic value of beaches have generally been undervalued (c.f. Bush et al., 2004; Schlacher et al., 2007). And even though beach nourishment is considered the most environmentally-friendly option for shore protection, myriad impacts at all spatial and temporal scales have been well documented in the scientific literature (c.f. Greene, 2002; Viola et al., 2014). Despite decades of expensive, agency-mandated monitoring, the cumulative effects of marine dredge and fill projects are still poorly constrained (Defeo et al., 2009; Peterson and Bishop, 2005; Wooldridge et al., 2016). Speybroeck et al. (2006) list several ecologically sound practices that could minimize the cumulative environmental impacts of beach nourishment including (1) the use of compatible fill and (2) construction of a number of small projects rather than a single large one. Given

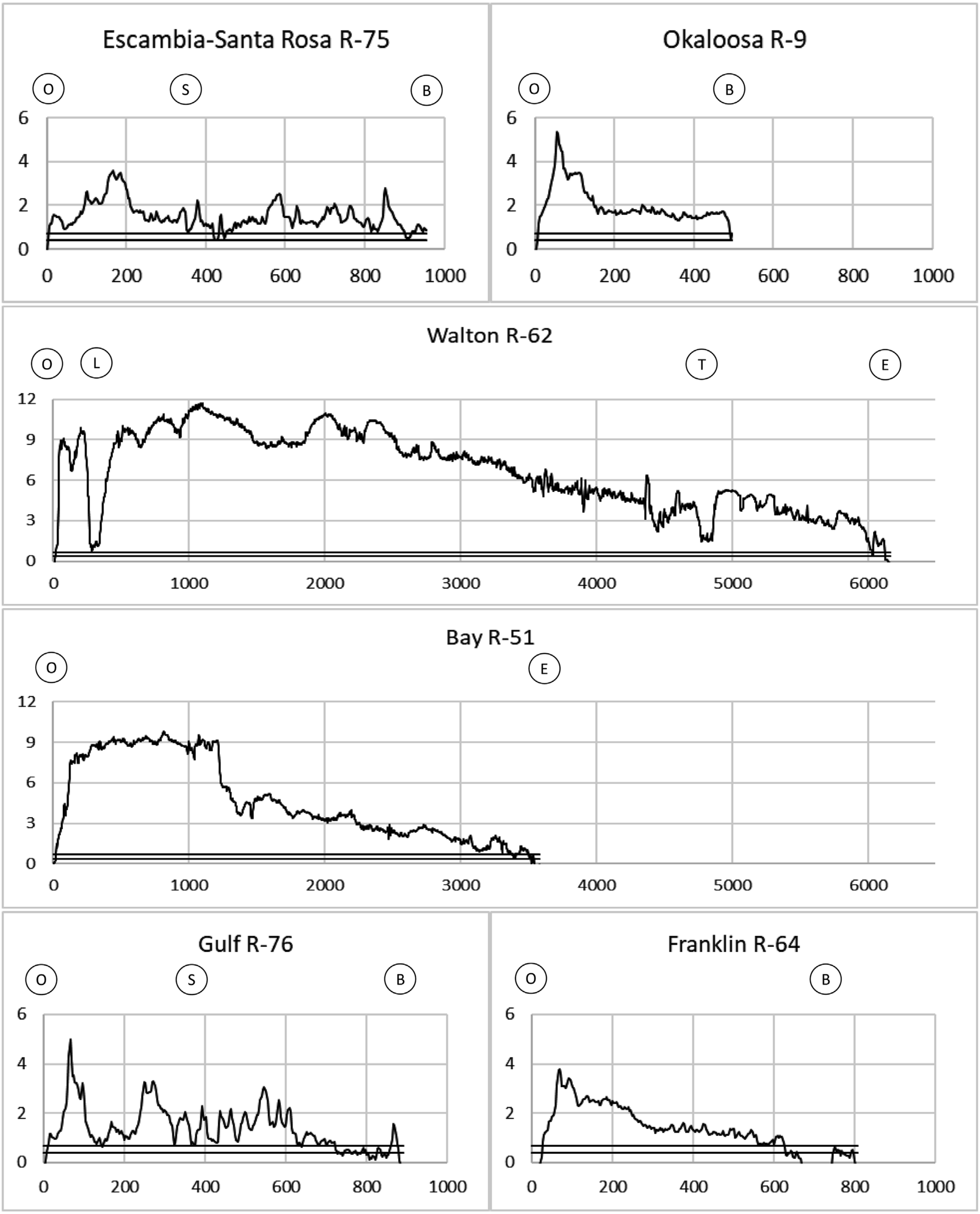

Fig. 5. Six randomly selected LIDAR-based topographic profiles (meters) constructed shore-normal to range monuments (R) installed and maintained by FDEP. Horizontal lines represent minimum (0.38 m) and maximum (0.68 m) range of sea level rise used by Houston (2017). In addition to the oceanic (O) shoreline, flooding and/or erosion will occur along the shoreline of swales (S), the backbarrier (B), lakes (L), tidal creeks (T), and estuaries/bays (E). See Fig. 1 for monument locations. Walton and Bay County scale (VE = 90) different from others (VE = 65).

Table 2
Components of published studies designed to evaluate the utility of beach nourishment as a viable strategy to mitigate climate change.

Location	Potential borrow areas	Native beach compatibility	Cost estimate	Geomorphic feature (s)	Environmental impacts	Source
Global	No	No	Yes (method could not be determined)	Oceanic shoreline	No	Hinkel et al., 2013
Australia	Yes (reconnaissance-level)	No	Yes (current market conditions)	Oceanic shoreline	Yes (conceptual)	Langedijk 2008
Europe	No	No	No	Oceanic shoreline	No	Hamm et al., 2002
Japan	No	No	No	Oceanic shoreline	No	Yoshida et al., 2014
USA	Yes (reconnaissance-level)	No	Yes (current market conditions)	Oceanic shoreline	No	Leatherman 1989
USA	Yes (conceptual)	Yes (conceptual)	No	Oceanic shoreline	Yes (conceptual)	NRC 1987
Florida panhandle, USA	No	No	No	Oceanic shoreline	No	Houston 2017

what is currently known about the compatibility of Florida panhandle's marine sand reserves and the scale of nourishment required to mitigate climate change, it would appear neither of these strategies could be implemented. Furthermore, the scale of dredging required to generate the necessary sand volume is an order of magnitude larger than all projects constructed or permitted to date (Fig. 2). How will this be viewed by local stakeholders or State and Federal agencies charged with environmental and species protection?

8. Global implications

The literature is replete with discussions of the effects of climate change on the worlds' coastlines and the potential use of beach nourishment as an effective mitigation strategy. However, there appear to be only a limited number of published studies (Table 2) designed to consider the full range of ecologic, economic, technical details required to determine whether such a strategy is actually viable. All of these studies should be considered an important first step, but there exist several significant limitations to the scope of each that constrain their utility. For example, while the volume of sand required to mitigate erosion was always considered, in less than half of the cases were potential sand sources identified and in no case was the quality or quantity of sand evaluated at the appropriate level of detail. In only one study was the compatibility of fill considered relative to the native beach (es). While project cost estimates were included in three of the seven investigations, these relied upon current market conditions that cannot be used to develop an accurate projection of construction costs through the end of this century. In all cases, the investigators focused only on the oceanic shoreline; one of many potentially vulnerable geomorphic elements of the coastal landscape. And finally, the environmental impacts of beach nourishment were either omitted or discussed at the conceptual level of detail. Clearly, a more robust analysis of beach nourishment as a potentially viable strategy to mitigate climate change must be conducted before any adaptive management decisions are made at any level of governance.

9. Concluding remarks

Nourishment of oceanic beaches along the Florida panhandle to mitigate climate change at the scale proposed by Houston (2017) is simply not sustainable given available information about marine sand reserve compatibility, construction costs, risks posed to geomorphic features other than the oceanic coast, and living marine resources subject to repetitive construction events. A review of similar analyses conducted at global to regional scales indicates these limitations are not uncommon. It follows their conclusions regarding the viability of beach nourishment as a cost-effective, long-term management strategy to mitigate climate change are subject to question.

The nourishment of oceanic beaches as historically constructed will surely continue over the next several decades. But this must be considered a near-term strategy to address *existing* vulnerabilities associated with coastal erosion and inundation. In the long-term, the risks posed to most developed coastlines by climate change will ultimately have to be addressed by a robust, adaptive management strategy that incorporates managed withdrawal from the shoreline.

Acknowledgements

We gratefully acknowledge Florida Department of Environmental Protection, Division of Water Restoration Assistance Beach Funding and the Beaches, Inlets and Ports Program for providing assistance during the data mining phase of this analysis. Andy Coburn, Associate Director of the Program for the Study of Developed Shorelines, provided historical beach nourishment construction cost data for the Florida panhandle. This is Publication Number 15 of the Sea Level Solutions Center in the Institute for Water and Environment at Florida International University.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ecss.2018.07.011.

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