Sea level rise and consequences for navigable coastal inlets

By

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ABSTRACT

Global sea level is expected to rise over the next 100 years. Changes in sea level will alter the functioning of coastal inlet navigation channels and structures such as jetties designed to stabilize the channel and improve navigability. Threats to navigation at stabilized coastal inlets and intercoastal waterways caused by sea-level rise are identified and discussed. Concerns for navigation include jetty flanking (overwash on the shoreward terminus of the jetty); increased wave forces on the jetty trunk, possibly causing overwash and movement of armor stone; loss of capacity in subaerial dredged material placement sites; decrease in natural sand bypassing because of an effective increase in jetty length; decrease in clearance beneath bridges and overpasses; changes in patterns of channel shoaling; and increased landward migration of barrier islands. This paper discusses these phenomena and concludes with a recommendation for proactive assessment of coastal inlets with respect to sea level rise and potential consequences.

ADDITIONAL KEYWORDS: Jetty, navigation channel, flanking, erosion, overwash, breaching, stability.

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Sea-level rise (SLR) has received considerable attention with regard to coastal flooding and erosion, changes in marine habitat, and intrusion of salinity in city water supplies (Elko *et al.* 2009). In contrast, little consideration has been given to SLR and coastal inlet navigation channels, yet navigation channels are central to the commerce of all coastal countries. The present paper explores potential implications of SLR for navigable coastal inlets and their stabilization structures (principally, jetties). Because of readily available information, it is convenient to consider federal navigation projects in the United States, which are operated and maintained by the U.S. Army Corps of Engineers (USACE). The material covers existing stabilized inlets, but many of the findings apply to new navigable inlets.

The USACE is the world's largest public engineering agency, supporting national civil and military activities of the United States (USACE 2007). Its engineering regulations require change in sea level to be evaluated for all projects (environmental enhancement, flood protection, navigation related) within tidally influenced regions at the feasibility planning stage of project studies (USACE 2000, 2009a). The assessment is to be conducted for an economic period of analysis that is typically 50 years, and it is recognized that many USACE projects continue beyond their original authorized periods.

A major USACE mission is to provide safe, reliable, and efficient waterborne transportation within coastal, estuarine, and riverine systems (within authorized federal navigation projects). Federal navigation systems facilitate commerce, contribute to national security, improve estuarine functioning, and enhance recreational opportunities. Although not examined in this paper, some of the oldest federal navigation projects are located in the Great Lakes, which are expected to experience a decrease in water level over the coming century through change in global climate, resulting in an increase in navigation cost (Global Climate Change Impacts in the United States 2009).

For a coastal inlet, one that experiences waves, a tidal current, and perhaps a river current, a typical navigation project consists of:

1. A channel maintained by dredging extending from the estuary or bay to the sea.

2. Dual jetties to fix the location of the inlet, promote channel scour, and minimize navigation hazards.

3. Dredged-material placement sites that may include areas for bypassing dredged beach-quality sediment to the down-drift beach or nearshore.

4. Connecting channels and waterways into an estuary, bay, and river.

Some navigable inlets have one jetty or no jetties, and some have breakwaters for wave blocking or sediment retention. Discussion herein is based on the paradigm of a dual-jetty inlet. Navigation structure terminology is discussed by Kraus (2005). Dredged-material placement sites often serve several purposes. They can (1) be a repository for the dredged sediment; (2) create nearshore berms that dissipate wave energy and bypass sand to the adjacent beaches; and (3) provide an environmental enhancement opportunity through creating and maintaining wetlands, bird habitat, and historic islands that have been degraded by erosion and sea level rise.

This paper explores potential benefits and detriments to functioning of coastal inlet navigation systems that may accompany a rise in sea level. Means of planning for and coping with this process are also discussed.

SEA LEVEL RISE

Global or eustatic sea level is anticipated to rise within the next 100 years, with projections ranging from 1.6 ft to 4.9 ft (National Research Council (NRC) 1987) and 0.55 ft to 1.9 ft (Bindoff *et al.* 2007) in two well-cited studies. Based on available tidal records at the time, NRC (1987) estimated a rate of eustatic sea level rise equal to 0.4 ft per century, although more recent analysis of longer

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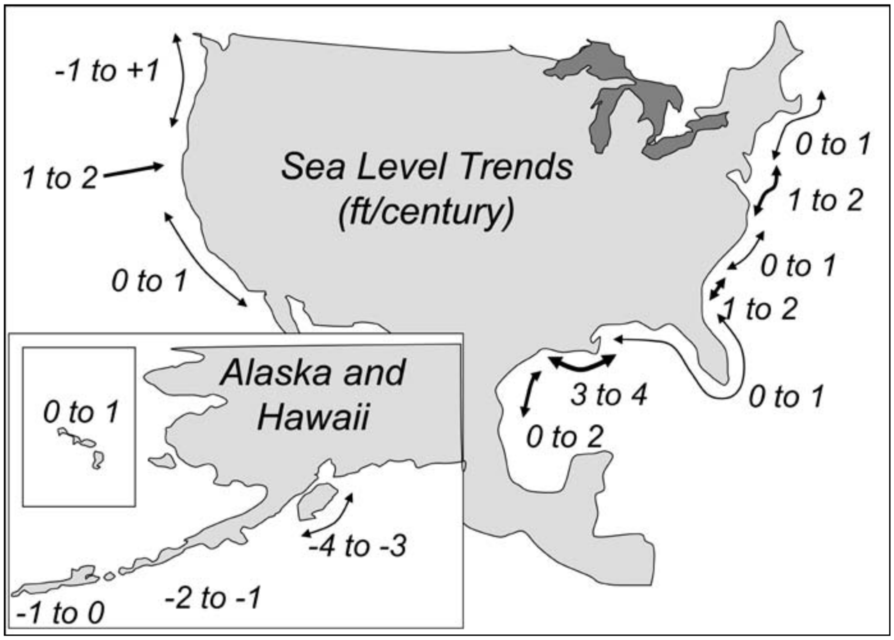

Figure 1. Trends in rates of sea level change (ft/century) in the U.S. based on long-term tide records (modified from NOAA 2008).

duration records indicates a rise of 0.56 ft per century (Bindoff *et al.* 2007). Relative sea level (RSL) refers to local elevation of the sea with respect to land, including the lowering or rising of land through geologic processes such as subsidence and glacial rebound. The rate of RSL change can vary from the eustatic rate of change. Figure 1 schematically summarizes rates of RSL change in feet per century based on long-term tidal records (greater than 30 years) for the United States. This figure indicates RSL rise along most of the Atlantic Ocean and Gulf of Mexico coasts, and primarily rising RSL on the Pacific with the exception of some of the northern-most coastlines. Sea level undergoes annual and seasonal changes that can be comparable to and even exceed the mean long-term trend, not discussed further here. A negative value in Figure 1 indicates that land is rising with respect to sea level (relative sea level fall).

The NRC (1987) presents an equation to estimate future SLR based on three curves bracketing a range in eustatic change, the historic local RSL rate, and an implied starting date of 1986 (the time of the NRC report). Adapting the equation for future starting dates gives (modified from Knuuti 2002):

$$E(t_2) - E(t_1) = e(t_2 - t_1) + b(t_2^2 - t_1^2) \quad (1)$$

in which $E(t_1)$ and $E(t_2)$ are the eustatic sea levels at times t_1 and t_2, t_1 is the time between the start time and 1986, t_2 is the time between the ending time and 1986, e represents the historical rate of eustatic sea level rise, and b is a coefficient representing each of the three NRC curves as shown in Table 1. Setting the coefficient b equal to zero assumes that there will be no increase in the rate of eustatic sea level rise.

Applying Equation (1) in 2010, for a project life of 50 years and historical rate of eustatic sea level rise e = 0.4 ft per 100 years (as cited by the NRC study), then t_1 = 2010 - 1986 = 24 years, t_2 = 2060 - 1986 = 74 years, and the increase in eustatic sea level at the year 2060 would be 0.65 ft, 1.3 ft, and 1.9 ft greater than that in 2010 for NRC Curves 1, 2, and 3, respectively (column 4 in Table 1). With a more recent estimate of the historical rate of eustatic sea level rise e = 0.56 ft per 100 years (Bindoff *et al.* 2007), the estimates increase by about a tenth of a foot for the 50-year period.

To calculate local RSL, Equation (1) is adapted to include site-specific sea level change data, following from NRC (1987) and Knuuti (2002):

$$RSL(t_2) - RSL(t_1) = (e + M)(t_2 - t_1) + b(t_2^2 - t_1^2) \quad (2)$$

in which $RSL(t_1)$ and $RSL(t_2)$ are the total RSL at times t_1 and t_2, and the quantity ($e + M$) is the local change in sea level in ft/year that accounts for the eustatic change as well as uplift or subsidence. The NRC method for calculating the estimated range of future sea level change is the method recommended by the USACE (2009a), with the exception that the historical rate, e, in Equations (1) and (2) has been updated to the rate cited by the Intergovernmental Panel on Climate Change (Bindoff *et al.* 2007).

Continuing with the example presented previously, a value of $e + M$ = 2.1 ± 0.09 ft/100 years increases the previous estimates for a 50-year project by 0.8 ft to 1.5, 2.1, and 2.7 ft greater than that in 2010 for NRC Curves 1, 2, and 3, respectively (column 5 in Table 1). This value of ($e + M$) is representative of Galveston, TX, on the bay side, where there is a long navigation channel (Pier 21 on the bay side of Galveston Island, National Oceanic Atmospheric Administration [NOAA] 2006). This example illustrates how local change in sea level can be on the same order as the eustatic rise in sea level for the NRC (1987) Curve 1.

RELATIVE SEA LEVEL IN COASTAL NAVIGATION PROJECT ASSESSMENT

Prior to the NRC (1987) study, USACE guidance for future rise in sea level was to extrapolate the local RSL rate into the fu-

Table 1. Values of coefficient b applied in Eq. (1) (adapted from NRC 1987) and examples discussed in text.

Curve	**Increase in eustatic sea level above 1986 level by 2100 (ft)**	***b* value in Eq. (1) (ft/year^2)**	**Examples for a 50-year project**	
			***e* = 0.4 ft/ 100 years**	***e* + *M* = 2.1 ± 0.09 ft/100 years (Galveston, TX, Pier 21)**
Historical rate*	0.46	0	0.20 ft	1.1 ± 0.05 ft
1	1.6	9.2×10^{-5}	0.65 ft	1.5 ± 0.05 ft
2	3.2	21.7×10^{-5}	1.3 ft	2.1 ± 0.05 ft
3	4.9	34.5×10^{-5}	1.9 ft	2.7 ± 0.05 ft

* Forecasting past eustatic sea level into the future with no anticipated acceleration.

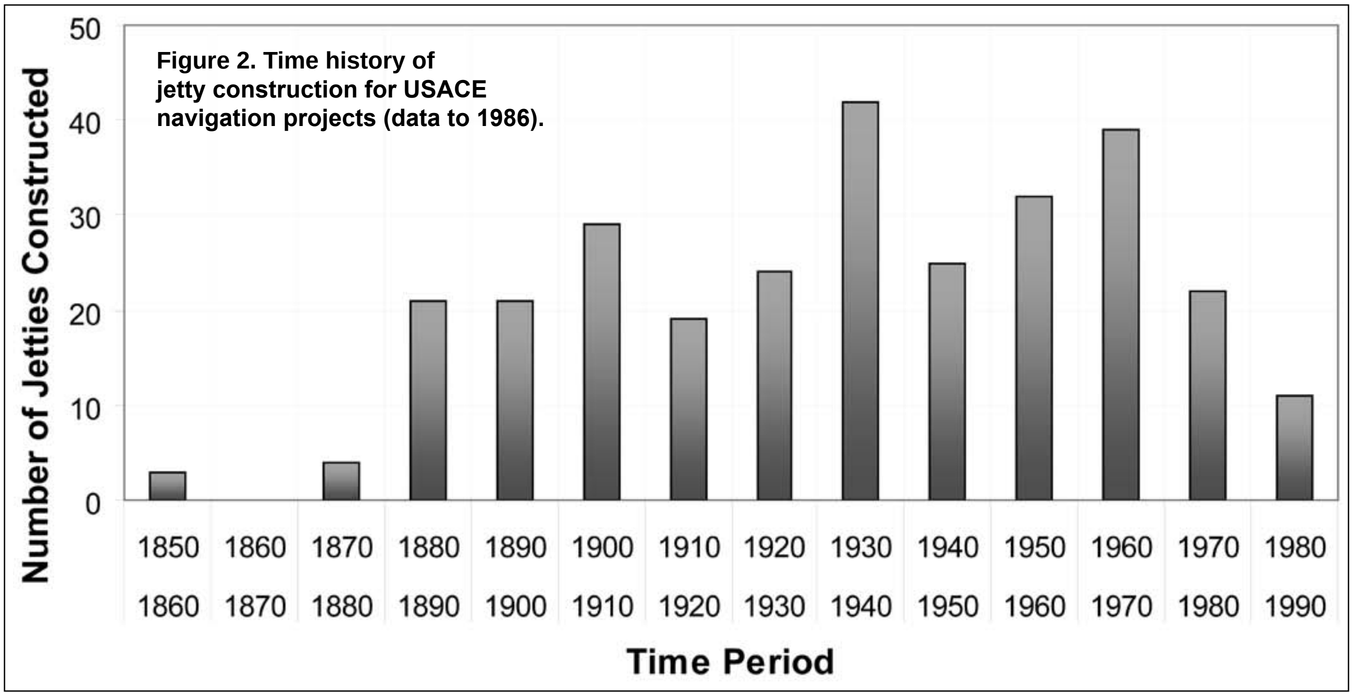

Figure 2. Time history of jetty construction for USACE navigation projects (data to 1986).

ture for the lifetime of the project. In year 2000 (USACE 2000), guidance required an assessment of potential future changes in sea level considering both local RSL rise (low estimate) and awareness of the potential increase in future eustatic sea level based on a high estimate from Curve 3 in the NRC (1987) report. The most recent guidance (USACE 2009a) recommends this same approach, with a value of $e = 0.56$ ft per 100 years in Equations (1) and (2). USACE (2009a) presents a methodology and two example calculations. Each project for which RSL will be a future consideration must conduct a sensitivity analysis with the low and high estimates. Adaptive management is required to facilitate future modifications unless the structure is unusually high cost and not well-suited to alteration, such as flood gates or storm barriers intended to reduce storm surge into a protected region. For these types of structures, the design would incorporate the maximum sea level anticipated over the project life.

With present USACE guidance, a project planned for construction in 2010 and designed for a 50-year life in vicinity of Galveston, TX, would consider response of design alternatives to a RSL increase between 1.1 ft (historical rate of RSL rise, Table 1) and 2.7 ft. With all other performance criteria assumed similar, the concept is to select the design that is most easily adapted to the anticipated change in sea level. For example, Kraus *et al.* (2008) considered implications of RSL rise in functional design of a new jetty at the mouth of the Colorado River, TX, and discuss flanking, water- and wind-borne sand transport into the channel at the seaward end of the jetty, and increased wave loading on the jetty accompanying an increase in sea level.

SEA LEVEL AND NAVIGATION PROJECTS

This section explores how an increase in sea level can degrade or benefit navigation projects given their present condition and maintenance by dredging. The elements of navigation projects that could be influenced by SLR, depending on particular site conditions, include jetty flanking (overwash on the shoreward terminus of the jetty); increased wave forces on the jetty trunk, causing overwash and movement of armor stone; loss of capacity in subaerial dredged material placement sites, and increase in capacity for subaqueous sites; decrease in natural sand bypassing through an effective increase in jetty length; decrease in clearance beneath bridges and overpasses, and other impacts to fixed port and harbor infrastructure; and changes in patterns of channel shoaling. Water depth on NOAA navigation charts and to be followed in USACE projects for tidally influenced areas is referenced to the tidal datum Mean Lower Low Water (MLLW) (USACE 2009b).

JETTIES

Structure Age

Jetties, particularly at deep-draft navigation channels, can be considered as semi-permanent infrastructure. It is difficult to conceive of disassembly and removal of jetties. Of the 292 coastal jetties documented in the USACE structure database (USACE 1986), approximately one-quarter were constructed more than 100 years ago (Figure 2). Accounting for only eustatic sea level rise during this 100-year period, jetty crest freeboard (difference between crest elevation and water surface elevation) at many of these structures has decreased between 0.4 ft and 0.6 ft. Relative change in sea level because of local subsidence would further decrease the structure freeboard.

As an illustration, the Houston-Galveston jetties were constructed from 1887 to 1898 (Sargent and Bottin 1989) at an elevation of 5 ft relative to the USACE Galveston District navigation datum Mean Low Tide (approximately 5.3 ft MLLW), for the north and south jetties, respectively. During the approximately 130 years since construction, RSL has reduced the freeboard of the structures by 2.7 ft. The structures have also been damaged during storms, which dislodged armor stone. To mitigate for the loss in elevation, the structures have been rehabilitated several times, with the most recent repair raising both jetties approximately 2.6 ft to 4.3 ft from 1962-1966 (Sargent and Bottin 1989). In the next 50 years, the anticipated increase in RSL from 1.1 ft to 2.7 ft will require additional rehabilitation to increase the elevation of the outer armor and internal core stone by this magnitude. If larger

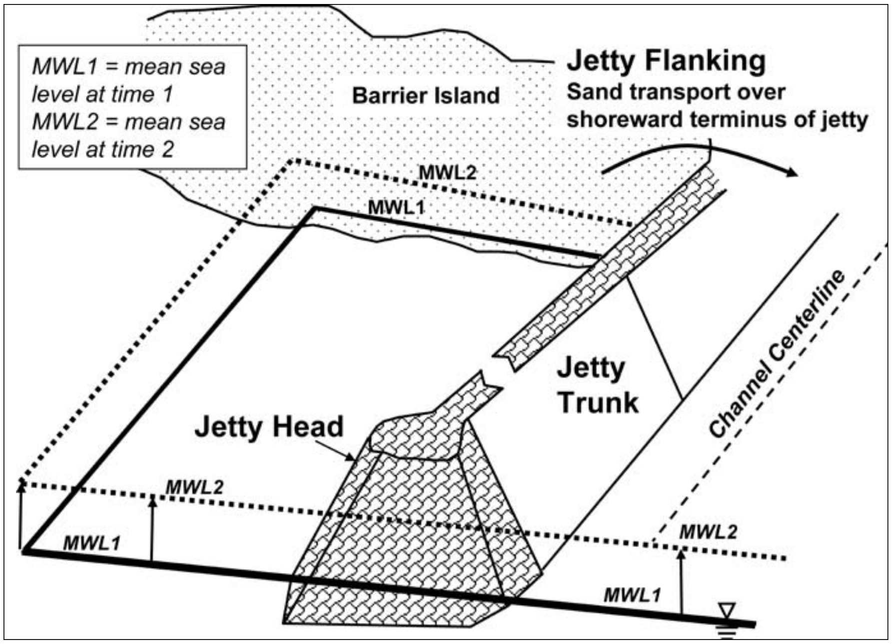

Figure 3. Schematic of sea level rise at a jetty.

waves are expected to strike the structure with the increase in RSL, the size of the armor stone may increase beyond that of the original design. As an adaptive strategy, the shoreward portion of the structures could be rehabilitated first, with the seaward portion considered for rehabilitation if channel shoaling and navigation hazards require additional elevation. For structures placed on a relatively soft substrate, the weight of the stone induces an additional loss in elevation that is estimated in design. Because the cost of jetty construction or rehabilitation is proportional to the volume and size of stone placed, RSL rise brings an increase in stone volume and potentially size needed and, therefore, an increase in construction cost.

Flanking

Jetties are typically tied to or connected to shore for a certain distance landward. A jetty may also connect to a revetment that runs through the inlet. The instantaneous shoreline, defined as the intersection of land, sea, and air, moves with the water level. Contributions to the instantaneous water level are tide, change in mean water level by waves (called wave setup), run up on the beach by individual waves, wind set up or set down depending on cross-shore direction of wind, and storm surge. As sea level rises relative to the landward end of a jetty, during conditions of higher waves, onshore wind, and higher tide, water may flow over the jetty and transport beach sand into the inlet and navigation channel, thereby isolating the jetty in a process called flanking (Figures 3 and 4).

Intermittent jetty flanking is becoming more common. If flanking persists, the jetty may become isolated from land and a new channel formed that can compete with the main navigation channel. The new opening may capture a significant portion of the tidal flow (Figure 4). Depending on the size of the inlet, beach sediment may be deposited in the inlet and navigation channel, creating an alternate route for tidal exchange and eroding the adjacent beach. The landward crest of the jetty needs to be sufficiently high to prevent transport of sediment over it from both the wind and water, when the jetty might be overtopped or submerged, at least during typical sea conditions (Kraus *et al.* 2008). Extending a jetty landward and raising it to a sufficient elevation may be a relatively low cost preventative measure for vulnerable sites.

Although not part of the coastal inlet navigation system, the response of the adjacent beach to a navigation project must be considered within a regional sediment management approach over the lifetime of the project. If the project is determined to have caused adverse erosion of adjacent beaches, federal responsibility for the percentage of erosion caused by the navigation project can be assessed through what is called a Section 111 study, resulting in beach nourishment or bypassing to prevent or mitigate damages. Cost sharing for the damage prevention or mitigation is cost shared with the local sponsor under a Section 111 agreement.

Overtopping

Wave overtopping of jetties and breakwaters at navigation channels will increase with a decrease in structure freeboard. The additional waves and water in the navigation channel may hinder navigation, and overtopping of jetties and breakwaters with a secondary recreational function such as a fishing walkway could restrict public access during times with elevated waves and water level.

Weirs

A relatively small number of federally maintained inlets include a weir jetty. A weir is a low section of an up-drift jetty built with the intent of allowing sand transport over the structure and into a semi-protected area that can be dredged more readily than in the open sea (Seabergh 2002). The elevation of a weir is based on a number of parameters including tide range, predominant wave height, sand transport rate into the weir, and the relative strength of the ebb and flood tidal currents. With an increase in sea level, weir jetties will allow more waves, current, and sand to penetrate to the navigation channel, potentially exacerbating erosion up drift of the weir, increasing dredging requirements in the deposition area, and reducing navigation reliability. Weir sections will require rehabilitation to increase elevation and possibly adjust their location relative to the shoreline.

Structural Damage

Rubble-stone and fitted-stone jetties, common in the United States, are usually designed with a head on the seaward end built of larger stone than the trunk to withstand direct attack by waves. In shallow water, wave height is depth limited, and the deeper area of a jetty head must resist the larger forces exerted upon it by larger waves (Figure 3). As sea level rises, the trunk of the jetty will become increasingly exposed to larger waves and wave forces. Therefore, the structural integrity of jetties is expected to decrease with increased RSL. There is a compensating factor; if a jetty becomes submerged, as during a storm surge, waves might only partially break on it, reducing the wave force. However, other factors come into play, such as increased current through the upper level of the structure during

Figure 4. Example of flanked jetty at Mezquital Inlet, Mexico, creating channel competition to the Gulf of Mexico. (Photograph by N.C. Kraus, 1996.)

a storm, which would tend to dislodge stone or armor units.

Increased Effective Length

A rise in sea level will systematically move the location of the shoreline landward, thereby increasing the length of a jetty in the water. Longer jetties imply greater impoundment on the up-drift side and greater erosion on the down-drift side of an inlet, all other factors being constant. The seaward ends of the jetties will be in a greater water depth, decreasing the amount of sand that can be transported around them by longshore and tidal currents, decreasing natural bypassing around the ebb-tidal delta and by tidal bypassing. Although the navigation channel may experience less sediment infiltration because of the increased length and protection by jetties, the need for mechanical bypassing of beach-quality sediment to the down-drift beach would increase. Correspondingly, breakwater freeboard decreases with increasing sea level, thereby increasing wave penetration and sediment transmission through the structure, and reducing effective protection.

CHANNELS

Channel shoaling

The obvious change for a channel will be slight increase in depth through time until the MLLW datum is adjusted to present sea level, which would increase ship clearance relative to the sea bed and be a benefit to navigation. Other changes to the navigation system might override this benefit, including an increase in wave height (neglecting consideration of the wave and current interaction) and a potential increase in shoaling because of structure overwash and flanking (Figure 3). A more subtle consequence of SLR is a potential increase in shoaling because of salinity intrusion further into rivers and estuaries, which could promote flocculation and deposition of fine sediment that presently is transported seaward (NRC 1987). Erosion of the estuarine shores may also increase if the wetted perimeter expands, resulting in more sediment transported into the estuary. In many locations, fine clay and silt in fresh water suspension flocculates as it reaches the salt water wedge. With an increase in global sea level, the salt water wedge will move further upstream, and the hydraulic head between the river and the sea will decrease slightly, thus reducing the flow velocity carrying suspended sediment. The result will be a change in the location of estuarine shoaling and an increase in flocculation of fine sediment.

Change in water depth and effective lengths of the jetties will alter the tidal prism (see next section) and change the relative locations of breaking waves and circulation and sediment transport patterns at the inlet. The locations, shapes, and volumes of morphologic features such as ebb-tidal deltas, flood-tidal deltas, and traditional locations of channel infilling will respond to the modified forcing. Such changes will require adjustments in dredging practice, change distances to placement sites, and perhaps change access to sources of beach-quality sediment for bypassing. As an example of the latter process, in year 2002 the seaward section of south jetty at Ocean City Inlet, MD, was raised and sand tightened. This modest rehabilitation effectively lengthened the jetty. As a consequence, the margin of the ebb-tidal delta, which serves as a source for mechanical bypassing to the down-drift beach, migrated further landward with focus of the ebb-tidal current (Buttolph *et al.* 2007).

Navigation under bridges

As pointed out in NRC (1987), clearance under bridges spanning tidal water will gradually decrease with SLR. NRC (1987) notes that the reduction in clearance may be greater for bridges over arms of estuaries because of funneling of the current between narrowing land masses. SLR may at first be accommodated by vessel transit during lower tide, but through time the need for raising the bridge will have to be considered.

DREDGED MATERIAL PLACEMENT SITES

Rising sea level can provide opportunities for beneficial uses of dredged material, as well as change the capacity of placement sites depending on whether they are subaqueous (increase capacity) or subaerial (decrease capacity). Beneficial uses include creation and preservation of wetlands, re-establishment or improvement of historic islands, creation of bird islands, and bypassing of beach-quality dredged sediment to both sea and estuary beaches. It is a challenge to maintain wetlands at an elevation such that they receive tidal inundation necessary for their functioning.

Typically, the plan-view footprint of authorized designated placement sites is fixed. The capacity of these sites might increase or decrease with rise in local water level, depending on configuration and location. As sea level rises, placement sites can become more vulnerable to damage during storms (Tirpak 2009), and an increase in dredging and placement requirements would shorten the life of the site.

Another beneficial use of beach-quality dredged material is to bypass it to the beach adjacent to the down-drift jetty. A justification for the navigation project would be to protect existing infrastructure through reduction of potential for flanking, with a secondary benefit to the adjacent beach. Suitable dredged material may also be stockpiled as a "breach contingency plan" (USACE New York District 2009) to facilitate rapid closures of breaches in barrier beaches as might occur adjacent to navigable inlets.

REGIONAL AND ANTHROPOGENIC CHANGES

Many deep-draft channels will be deepened, widened, lengthened with increase in size of the worldwide shipping fleet. Such changes are expected to increase channel dredging maintenance volume, increase the need for extending the capacity of placement sites and development of new placement sites, and require possible modification of the jetties. The natural counterpart to channel deepening by dredging is an effective deepening with SLR, with consequences in particular for the estuary behind the inlet with potential increases in bay area, tidal prism, and shoal volumes, and salt water intrusion.

As an extreme example, over the past 100 years Barataria Bay, LA, has experienced a combination of wetland loss and a RSL increase of approximately 3 ft (FitzGerald *et al.* 2007). The result has been an increase in bay area, tidal prism (volume of water entering or exiting an inlet during a tidal cycle), and inlet shoal volumes. The source of sand for the inlet shoals has been the adjacent barrier islands, increasing island segmentation and breakup (FitzGerald *et al.* 2008). Walton and Adams (1976) introduced empirical formulas relating the volumes of ebb shoals and the tidal prism. Similar, but less statistically confident relationships for the volumes of flood shoals also exist (Carr de Betts 1999). Increase in tidal prism will cause an increase in shoal volume, and the material for this will in great part originate from the adjacent sea sides of the barrier beaches. Kraus (2009) discusses other morphologic responses to coastal inlets.

BARRIER ISLAND MIGRATION

Narrowing of barrier islands under SLR and their possible landward migration through overwash effectively lengthens jetties, bringing the problems of flanking and a decrease in natural bypassing as discussed above. Landward migration of barrier islands would reduce the surface area of the estuary, assuming other parts of its perimeter are hardened with infrastructure and cannot migrate landward, thereby decreasing the tidal prism. If the tidal prism decreases, some portions of the ebb shoal may migrate on shore, strengthening the beaches adjacent to the navigable inlet, or become abandoned in deeper water and removed from the natural bypassing system by waves and wave-induced current (FitzGerald *et al.* 2008; see also references in Kraus 2009).

CONCLUSIONS

This paper has examined possible consequences of sea level rise for coastal inlet navigation systems. Most changes expected due to increased water level were found to be detrimental, such a jetty flanking, reduction of natural sediment bypassing, degradation of jetty integrity, increased cost of jetty rehabilitation, and increased need for dredged material as a resource for beneficial use. Some positive outcomes with an increase in sea level include increases in the navigable depth of channels and potential capacity of subaqueous dredged material placement sites.

Observations from long-term tide gauges around the United States indicate that sea level is rising over most of the Atlantic Ocean and Gulf of Mexico coasts. According to many authorities, eustatic or global sea level rise will increase the tendency for local sea level to rise. It is prudent to accommodate provision for sea level rise in an adaptive and long-term strategy for maintaining navigation channels at and around coastal inlets. Many federal jetties are more than 100 years old, the time scale of planning for sea level rise, and they will continue in service. Present USACE guidance for new projects is to consider a range in possible values and design for adaptation, with certain exceptions.

It is recommended that jetty elevation, condition of the adjacent beaches (considering flanking and water- and wind-borne sand transport), channel depth required for navigation, and dredged-material placement sites be evaluated from the perspective of functioning with a rise in sea level. Such an evaluation would assist in rehabilitation of structures as the opportunity arises, as well as in the modification of existing and construction of new jetties and breakwaters at inlets. The adaptive management can be collaborative among federal and local agencies for long-term planning such as modifying jetties, utilization of dredged material for benefiting the environment, designating dredged-material placement sites, adapting infrastructure at ports and harbors, and raising bridges spanning coastal inlets. Such planning would coordinate among cost-sharing sponsors in providing information about expected actions and associated costs at coastal navigation projects.

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