Defining beaches and their evolutionary states in estuaries

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ABSTRACT

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Projected rates of global sea level rise and human pressures have increased attention to the potential for landform change in estuaries. This paper assesses the status of the fetch-limited beaches in the Tagus estuary, one of the largest estuaries in Europe, with a focus on distinguishing active beaches from inactive vegetated banks and identifying conditions under which they change state. A total of 26 beaches were identified in the inner estuary and 49 in the tributary basins on 2007 aerial photographs and compared with conditions on older photographs (1944-1958). Lengths, widths and maximum fetch distances for beaches were measured and site visits were made to determine their origins and present conditions. Beaches occur at eroding uplands or marshes or on spits extending from eroding uplands. Human-created beaches occur on spoil areas, within niches formed by structures and where vegetation is eliminated or prevented from colonizing (e.g. boat launches and recreational surfaces). Basin infilling, with increase in the elevation of low tide terraces and the formation of bars, is reducing wave energies, and some beaches are reverting to vegetated banks. Beaches that become vegetated banks because of human actions occur where use for boating or recreation is abandoned and where spits that form off spoil deposits reduce fetch distances upwind.

ADDITIONAL INDEX WORDS: *Wave energy, fetch distances, sedimentation rates, human interventions, Tagus estuary.*

INTRODUCTION

Local fetch distances and availability of suitable sediment help define the role of waves in reshaping coastal formations into beaches. Fetch distances in estuaries are determined primarily by the configurations of basin interfluves and secondarily by accretional features, such as spits and bars. Beaches in estuaries are opportunistic landforms that are highly variable in terms of size, orientation and relationship to cultural features. They occur primarily where the combination of suitable unconsolidated sediment and exposure to waves are sufficient to overcome the stabilizing effects of vegetation. Beaches are usually most conspicuous on the margins of open estuarine basins that have the greatest fetch distances, especially where sediment from readily erodible coastal formations or stream deposits is available, but they can also occur on the leeward margins of basins and in narrow tributary basins. Beaches can form and survive where fetch distances are less than 1 km (Nordstrom and Jackson, 2012), but the reason why beaches occur at the low energy end of the estuarine wave regime has not been a focus of study.

Projected rates of global sea level rise have increased attention on the potential for landform change in estuaries (Nordstrom and Jackson, 2012). Much of the recent attention has been on locations where inundation exceeds sedimentation and on loss of salt marsh habitat in particular (Orford and Pethick, 2006; Spencer and Brooks, 2012). However, sedimentation currently exceeds inundation rates in some estuaries. This condition leads to decreasing water depths that diminish the potential for wave generation across the basin and increase the potential for wave energy dissipation due to shoaling just bayward of beaches. Both of these processes can reduce sediment mobility on foreshores and increase the likelihood of vegetation growth on beaches where wave energies are already low. Recent studies of estuarine beaches have focused attention on the role of the low tide terrace as a significant factor in changes in landforms and biota on foreshores landward of them (Jackson and Nordstrom 1992; Jackson *et al.*, 2002; Kennedy, 2002; Eliot *et al.*, 2006; Smith *et al.*, 2011), but the significance of this feature on beach evolution has not been evaluated.

This paper assesses the evolution and status of beaches in the inner Tagus estuary and its tributaries (Figure 1), with a focus on distinguishing active from inactive vegetated foreshores and identifying the conditions under which they change from one to the other. The Tagus estuary is considered appropriate to evaluate this issue because of the many beaches in exposed and sheltered locations and the variety of human actions affecting them. The origin and long-term evolution of beaches in the Tagus estuary were discussed by Taborda *et al.* (2009). They presented a conceptual model relating the origin of estuarine beaches to the early Holocene post-glacial sea level rise that promoted the inundation of the lower Tagus basin. After the transgressive maximum, by 7,000 years BP, the rate of sea level rise decreased, favoring estuary infilling, and locally generated waves eroded the unconsolidated coastal formations promoting beach development.

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Figure 1. Location of the study area (image from: Bing Maps Aerial Imagery Web Mapping Service).

Recently, human alterations have influenced beach change (Taborda *et al.,* 2009). This study identifies how beaches change in decadal time spans and how human actions contribute to their formation and persistence.

STUDY AREA

The Tagus estuary encompasses 320 km^2 and is one of the largest estuaries in Europe. It is located in the Portuguese west coast, in the metropolitan area of Lisbon. Its margins are intensively occupied, with urban (34% of the total margin area) and industrial and port development (24%) on its western and northern sides, agriculture parcels (35%) on its eastern side and isolated towns and military facilities on its southern side (Rilo *et al.*, 2012). The estuary has a complex morphology with a deep and narrow fault-controlled inlet channel and a broad and shallow inner basin with a wide intertidal area (mudflats and salt marshes), covering about 43% of the total area (Nogueira Mendes *et al.*, 2012).

The average discharge of the Tagus River, the main source of fresh water into the estuary, is about 370 m^3 s^{-1} (Neves, 2010). The estuary is protected from ocean wave incursion by its narrow entrance, but the elongate shape of the inner basin in the prevailing wind direction, from the north, favors local generation of waves (Freire and Andrade, 1999). Maximum fetch distance is about 25 km and maximum observed wave heights are about 0.84 m, at a site with a fetch distance of about 12 km (Freire *et al.*, 2009). Ferry terminals are located just inside the inlets to the tributary basins. Wakes from ferries, and wakes from smaller boats using marinas well within these tributary basins, contribute to the local wave regime.

The estuary has a semi-diurnal tidal regime with a mean spring range of 3.2 m and a neap range of 1.5 m in Lisbon (Portela and Neves, 1994). The semi-diurnal tidal constituents are significantly amplified within the estuary due to resonance, and the estuary is strongly ebb-dominated (Fortunato *et al.*, 1999).

Bottom sediments are mainly from fluvial and local sources composed of fine material (predominately silt) and sands. The sands are distributed along the deeper channels and on beaches. Marine sediments are restricted to the estuary mouth and inlet channel (Freire *et al.*, 2007). Sandy beaches are mainly developed along the southern margin of the inner estuarine basin and at a variety of locations and orientations in four of its tributary basins: Judeu, Coina, Moita and Malpique (Figure 2). Coastal formations here are predominately Pliocene detrital deposits partially covered by Quaternary alluvial and sand deposits. Beach sediments are mainly quartz sands with a median diameter ranging from 0.41-0.87 mm. The gravel fraction can reach 15% (Freire *et al.*, 2007).

Comparisons of hydrographic charts show that the intertidal areas in the inner estuarine basin have an average sedimentation rate of 3.0 mm yr^{-1}; the main channels have a slightly erosional trend (average values of about -1.0 mm yr^{-1}), which results partly from dredging activities. Salt marsh sedimentation rates, determined from isotopic (^{210}Pb, ^{137}Cs) dating of sediment cores, vary between 0.7 and 2.2 cm yr^{-1}, with the higher values in the upper estuary (Freitas *et al.*, 2012).

Rates of sea level rise on the Portuguese coast, obtained from Cascais (Figure 1) tide gauge data analysis, are compatible with a sea level rise acceleration scenario (Antunes and Taborda, 2009; Antunes *et al.*, 2010): 2.1 mm yr^{-1} for 1990 decade; 2.6 mm yr^{-1} ($\pm$0.3mm yr^{-1}) for 2000 to 2009.

METHODS

Beaches were initially identified as light colored strips between darker water bayward and vegetation landward on 2007 aerial photographs in Google Earth and orthophotos from the *Instituto Geográfico Português* (IGP), both with 0.5 m spatial resolution. Sites were not identified as beaches unless the light coloration extended across a width that represented a reasonable approximation of the sloping intertidal zone (greater than about 3 m). Sites less than about 30 m long were not classified as beaches unless there was a clearly identifiable dry backshore, recognizable by a bright white tone. This procedure eliminated many sites where local die-back of vegetation produced a false signal of wave reworking. The dry backshore was assumed to be evidence of wave effects. Beach length, width and maximum fetch distance (shoreline to shoreline) within the estuarine basin were measured to within one meter using the ruler tool in Google Earth.

Representative beaches were visited in the field on 23 and 30 May 2012 to evaluate local conditions that determine origin and stage of evolution. Sites where there was doubt about whether the features identified on photographs were functional beaches were also visited.

Beaches identified on the 2007 photographs were compared with conditions observed on 1944-1958 aerial photographs. The quality of the old photographs was insufficient to derive accurate beach dimensions, but presence or absence of beaches could be determined for the 49-63 year period. All the information was gathered in GIS format.

RESULTS

A total of 26 beaches were identified in the inner estuarine basin, with five of these on the north side in the developed portion of Lisbon and 21 on the less-developed southern margin. A total of 49 beaches were identified in the tributary basins: 23 in Judeu, 7 in Coina, 7 in Moita and 12 in Malpique (Figure 2).

Beaches that appear to be due solely to natural conditions occur bayward of eroding uplands or marshes or on spits extending from eroding uplands. Beaches that appear to be due to human actions or are substantially modified by human activity occur: (1) bayward of spoil areas that contribute relatively large amounts of unconsolidated sediment; (2) fronting landfills; (3) within niches formed by shore-normal portions of structures (usually the tie-back ends of seawalls); and (4) on surfaces where boats are launched or recreational beaches are raked and vegetation is thereby eliminated or prevented from colonizing.

Twenty-three of the 75 beaches front eroding uplands or marshes; 10 front spits; 8 front spoil areas; 6 front landfills; 21 are in niches; 4 are at boat launch areas (another 2 boat launch areas also front landfills and are included in the 6 identified above); 2 front seawalls; and 1 appears to be artificially nourished. Fetch distances at beaches in the inner basin vary from 5,515 m (due to local sheltering of the site by a groin) to 25,266 m. Fetch distances at beaches within the tributary basins vary from 117 m to 6,277 m. Several beaches in the tributary basins face the open bay, with fetch distances up to 24,218 m, although it is questionable whether

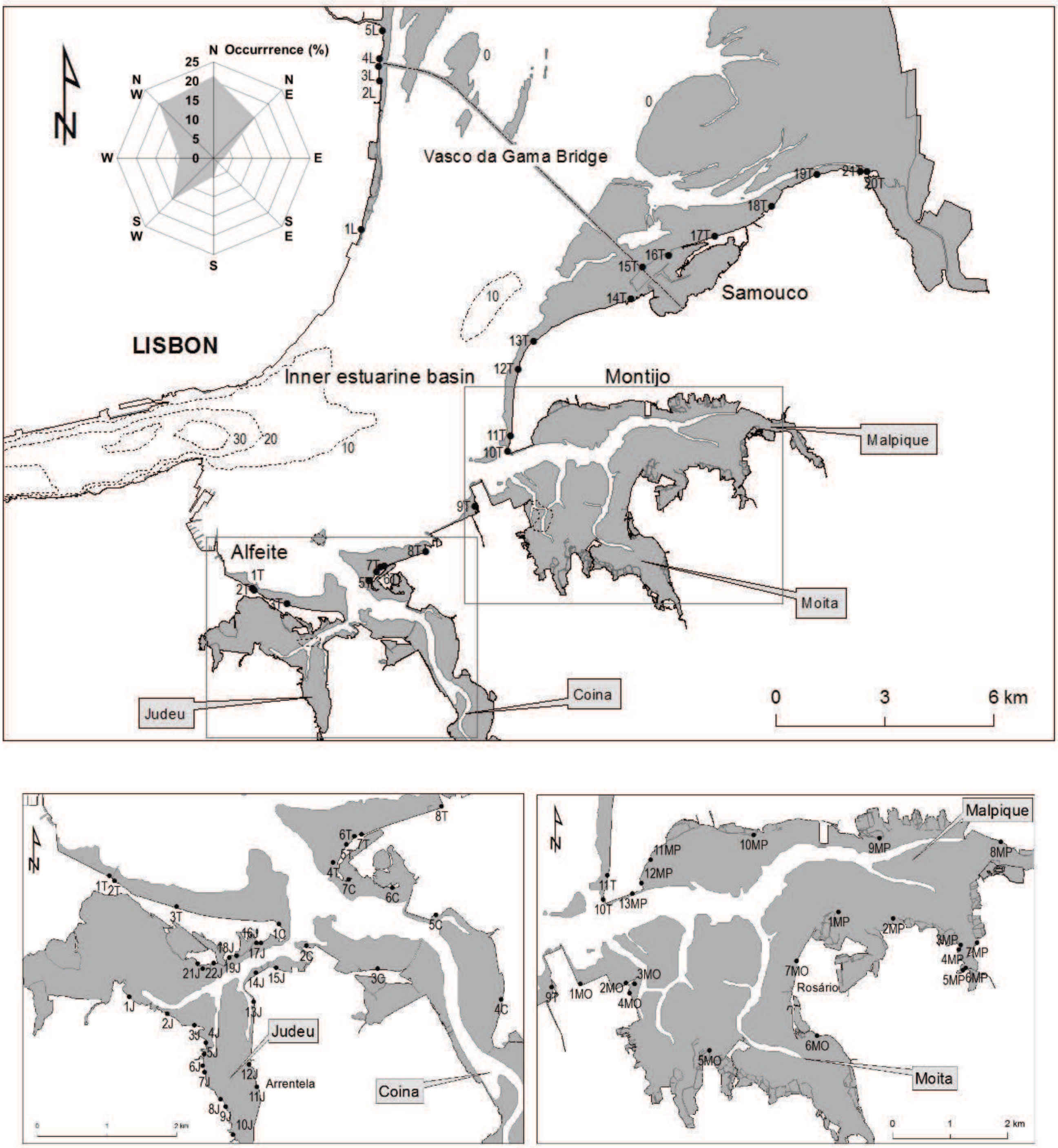

Figure 2. Beach locations at the inner estuarine basin (open bay), above. Below, detailed location of beaches in Judeu / Coina and Moita / Malpique basins. Bathymetry in meters relative to Chart Datum (2 m below Mean Sea Level). Wind rose represents the average annual wind regime (adapted from Oliveira and Vargas, 2009).

much of the wave energy from the open bay reaches these beaches through the inlets. The presence of many beaches in these sheltered locations is attributed to the unconsolidated sand in the coastal formations that is readily reworked by low-energy waves and to human actions.

Beach lengths in the inner basin vary from 32 m to 3,445 m. The longest beaches are at the Montijo military base and Alfeite (Sites 13T and 3T in Figure 2); the shortest beach is a boat launch location in the low-energy southeast corner of the inner basin (Figure 2, Site 21T). Four of the five beaches on the Lisbon side of the estuary are less than 100 m long and are in landfill locations that were part of the open bay in the 1950s. The longest beach on the Lisbon side (146 m) is a niche beach landward of a dock and appears to have formed as a tombolo from deposition of sand moved along the bay bottom in front of adjacent seawalls (Figure 2, Site 1L). Beaches in the tributary basins vary from 8 m to 1,540 m long. The shortest is a niche beach formed by abandoned human structures on the landward side of Alfeite spit (Figure 2, Site 16J); the longest is on the eroding upland at Rosário, facing the open bay (Figure 2, Site 7MO). Fetch distance within the tributary at this site is 3,103 m, but the distance to the Lisbon side through the inlet is 11,460 m.

Beaches in the inner basin vary from 5 to 28 m wide where they are not raked. The narrowest beaches are in the southeast corner of the estuary, where water depths are shallow and wave energy is low, and on the Lisbon side, where a seawall constricts landward development of the profile. Beaches in the tributaries vary from 3 m to 17 m wide within the local basins but are up to 26 m wide right at the entrances to the open bay where wave energies are greater and sediment is delivered through the inlet from the exposed side. The narrowest beaches are well within the tributaries, where fetch distances are short and wave energies are low. The widest beaches of all sites are raked to enhance recreation and are as wide as 73 m at the beach near Samouco in the inner basin (Figure 2, Site 14T).

The widest beaches are not necessarily the longest because human structures can break the shoreline into isolated drift compartments. The pronounced breaks in orientation within the tributary basins also contribute to beach compartmentalization. The great lengths of the beaches at the Montijo military base and Alfeite are due, in part, to those locations being within a single management unit, with no infrastructure close to the shoreline requiring protection against erosion. Exposure of those beaches to waves generated by northerly winds across relatively long fetch distances in the inner estuarine basin, combined with lack of barriers to transport alongshore, increase the area of beach habitat. Most of the other beaches, especially those within the tributary basins, have little area devoted to beach habitat because of longshore compartmentalization and limited cross-shore wave reworking.

A total of 50 of the 75 beach locations had beaches there in the 1940s and 1950s and, although the dimensions of most changed. Some of these beaches are longer than before; some are shorter because portions of them were eroded or the segment was divided by structures. Beaches now occur in 24 locations where no beaches existed in the 1940-1950s, mostly because fills to create new land or dispose of dredge spoil deposits converted water to erodible upland (Figure 3). In a few cases, existing beaches were lost because of burial by landfill, with new beaches forming bayward. Some of the new beaches are downdrift of landfills and are in niches created by human structures. Three of these beaches are at the Lisbon side in the fill for the Vasco da Gama Bridge (Figure 2, Sites 3L to 5L). Some of the former beaches were lost because of bulkhead construction, but some were converted to vegetated banks by natural vegetation colonization. A 433 m-long, 5 m-wide beach near Arrentela (Figure 2) that was exposed to a 2,630 m fetch is now marsh. The most conspicuous losses have occurred in the sheltered Coina Basin, where wave energies appear to have been too limited to prevent vegetation from colonizing former landfills.

Site visits indicate that vegetation colonization can occur due to development of coarser lag deposits that armor the beach surface or a reduction in wave energy due to deposition on the bay bottom or on low tide terraces, bars or spits fronting foreshores. One example of these processes is found near the southeast margin of the inner basin just east of Site 19T (Figure 2). Here, gravel derived from the eroding upland has armored the surface of the former beach and aided vegetation growth (Figure 4). Reduction in the ability of waves to rework the beach there is also attributed to sedimentation in the estuary that decreases water depths, leading to a reduction in the ability of winds to generate waves and an increase in shoaling on the fronting low tide terrace. Another example of vegetation colonization is occurring north of Site 4J (Figure 2). Extension of a spit extending from a spoil area at Site 3J has reduced fetch distance upwind of this site, leading to sedimentation in the shallow cove just offshore of the site. The reduction in wave energy is allowing slow colonization of the unvegetated intertidal zone (Figure 5).

DISCUSSION AND CONCLUSIONS

Results of this study reveal how beaches can change between active and inactive in the same estuary through natural processes and human actions (Table 1). Reduction in fetch distances by spit growth or deposition of dredge spoil upwind of beaches and dissipation of wave energy on the low tide terrace fronting beaches can increase the likelihood that vegetation growth will convert beaches to vegetated banks. Although not seen in this study area, abandonment of use for boating or recreation can also contribute to vegetation growth. Human actions can also convert beaches to vegetated banks where plants and sills are emplaced to stabilize the shore in "living shores" projects (Currin *et al.*, 2010; Walker *et al.*, 2011). Much of the literature on human alterations to coastal environments focuses on elimination of beaches due to replacement by human infrastructure or armoring by shore protection structures (Nordstrom, 2000). These processes have occurred on the urbanized coasts of many estuaries (Nordstrom 1992; Shipman, 2010) as has occurred on the northwest (Lisbon) side of the Tagus basin. Human actions can also create beaches intentionally or accidently, as is evident on the southern portion of the Tagus basin and its tributaries.

A traditional genetic definition of a beach as a geomorphic feature is "an unconsolidated sedimentary deposit created and shaped by waves." A functional definition, based on the goods and services a beach provides, may differ in that the deposit need not be created by waves if it can subsequently evolve by wave action. This functional definition is becoming a more apt descriptor through time on low energy and high energy beaches alike as more beaches owe their origin to beach nourishment and dredge spoil disposal operations. In estuaries, human actions can create beaches where they otherwise would not occur by preventing incursion of vegetation by direct disturbance through raking or boat launch or indirectly by supplementing wave action by boat wakes. The presence of many beaches in low energy environments in the tributary basins of the Tagus estuary system is, in part, attributed to the abundant sand in the coastal formations that provides a source of readily-reworked sediment, but humans have increased the potential for beaches to evolve where fetch distances are short. The many structures that extend out into the water

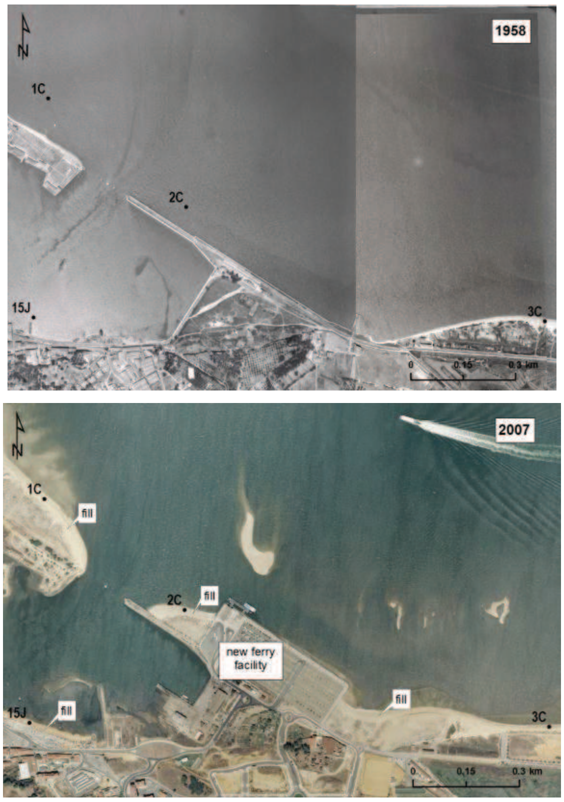

Figure 3. Changes in the shore near the entrances to Judeu and Coina basins.

provide traps that can accumulate even limited quantities of sediment moving alongshore. On exposed coasts, sediment trapping is commonly associated with shore-perpendicular groins and jetties that are designed expressly for this purpose and are built to withstand attack by high-energy waves. Many of the structures on estuarine shores were never designed to act as sediment traps, and many are now abandoned but remain to accumulate sediment because the wave energies are too low to break them up.

Figure 4. Sandy beach located near the Site 19T in the 1950s (left) and the same location on 23 May 2012 (right).

The overall form of the estuary is dependent on past geological conditions that have resulted in a north-northwest/south-southeast trend to three of the four tributary basins. The prevalence of strong winds from the northerly quadrants (wind rose in Figure 2), may contribute to the presence of beaches on the south sides of these basins. This exposure may help maintain beaches at Sites 4J to 10J that are well within the Judeu basin, where fetch distances normal to the shorelines are less than 1 km and winds from the east are infrequent. Fetch distance is not the dominant control of beach presence in fetch restricted estuarine basins, however. Only one of these seven beaches is a naturally-eroding upland. Human additions to the sediment budget, interference with vegetation growth and placement of cross-shore obstructions to sediment transport, combined with the addition of boat wakes to the wave regime, can override natural constraints.

Table 1. Factors contributing to formation of sandy (active) beach or vegetated (inactive) bank (effect of factor in parenthesis).

Favoring beach
Natural factors
Wide fetch (facilitates wave generation)
Deep basin (facilitates wave generation)
Deep fronting terrace (limits wave dissipation)
Sea level rise (increases upland erosion, adding sediment)
Unconsolidated sand in coastal formations (sediment easily reworked)
Human factors
Boat wakes (increase wave input, overcome fetch constraints)
Raking, boat launch (destroys stabilizing vegetation)
Nourishment/spoil disposal (adds sediment, buries vegetation)
Structures on beach (trap sand moving alongshore)
Favoring vegetated bank
Natural factors
Narrow fetch (restricts wave generation)
Shallow basin (restricts wave generation)
Shallow fronting terrace (increases wave dissipation)
Sedimentation rate<sea level rise (restricts upland erosion, favors basin infilling)
Limited sand in coastal formations (restricts input of mobile sediment)
Human factors
Vegetation planting (restricts sediment mobility)
Erosion control projects (stabilize shore, favor plant growth)

Figure 5. Site north of Site 4J, where vegetation colonization is occurring due to increased sheltering by growth of a spit at Site 3J upwind of it (picture taken on 30 May 2012).

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