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ORIGINAL ARTICLE

Influence of configuration of bulkheads on use of estuarine beaches by horseshoe crabs and foraging shorebirds

Nancy L. Jackson[1] · Karl F. Nordstrom[2] · Sherestha Saini[1] · David R. Smith[3]

Abstract Construction of bulkheads is a common response to erosion of estuarine shorelines. Bulkheads are usually built incrementally, resulting in wider sandy beaches remaining as enclaves between bulkhead segments. This paper measures the characteristics of bulkheads and enclaves and evaluates (1) whether horseshoe crabs (*Limulus polyphemus*) utilize enclaves for spawning when they provide partial sheltering during periods of high wave energies; and (2) whether eggs become trapped in the enclaves and are available to shorebirds when the beaches in front of bulkheads are inundated. The characteristics of bulkheads and beach enclaves were identified in five developed reaches in Delaware Bay, USA. Counts of horseshoe crabs were made in enclaves in two of these reaches during times of high wave energies and compared to counts in nearby unarmored segments. Egg tracer and trapping experiments were conducted at one of the enclaves to assess egg movement. Results indicate that the percent of bulkheads intersecting the beach below midforeshore varies from 10 to 50 %. Spawning densities were greater in enclaves than on longer unarmored segments on some days. Enclaves serve as a sink for eggs moving along the base of the bulkheads. Most birds feeding on horseshoe crab eggs preferred sites outside the enclaves and bulkhead segments. Any advantage of bulkheads creating enclaves and sinks for eggs moving alongshore is likely overridden by their disruption to natural process and habitats, but having unarmored enclaves between bulkhead segments may be preferable to one continuous bulkhead, based on environmental benefits.

Keywords Egg transport · Horseshoe crab · Shorebird · Shore protection · Sand beach · Delaware Bay

Introduction

Human and natural stresses are increasing on coasts through time (Frihy et al. 2010; Dugan et al. 2011). Coastal engineering structures add to these stresses by altering wave processes, interrupting longshore exchanges of sediment and creating a variable pattern of shoreline responses (Frihy et al. 2010; Infante et al. 2012; Merlotto et al. 2014). Human alteration of shorelines using shore-parallel protection structures (seawalls, bulkheads and revetments) can eliminate or fragment intertidal habitat and reduce suitability for species that rely on this environment (Villard 2002; Goodsell et al. 2007). The interaction of waves with shore-parallel structures can result in an increase in wave reflection, turbulence, sediment activation, nearshore current velocities, and longshore sediment transport at the base of the structure (Kraus 1988; Plant and Griggs 1992; Kraus and McDougal 1996; Miles et al. 1997). Many investigations of the effects of shore-parallel structures on intertidal biota in estuarine and exposed ocean environments focus on the fronting beach foreshore. Increased sediment activation and erosion in the vicinity of the structure can lower the abundance of interstitial fauna (Spalding and Jackson 2001). Elimination of the beach due to the presence of the structure can reduce wrack accumulation, decrease the

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abundance of mobile macro-invertebrates, decrease the number of foraging or roosting shorebirds, and decrease the success of species that spawn on the beach (Dugan et al. 2008).

Economic losses due to natural disasters have increased dramatically through time because of increases in the number of people moving to coastal locations and the frequency and severity of hazard-related events (NRC 2014). Superstorm Sandy, a coastal storm that occurred on the northeast coast of the USA in 2012, revealed the vulnerability of estuarine shores to flood damage and generated increased interest in finding ways to protect bay-shore infrastructure against flooding and erosion. Bulkheads are often used in estuarine environments to prevent coastal erosion and flooding, because they can withstand direct attack by the relatively low energy waves, are affordable, do not require much space, and need not alter the bay bottom (Macdonald et al. 1994; Nordstrom 2014). Increased use of structures in estuaries is a serious concern for the sustainability of coastal resources (NRC 2014). Finding ways to protect human infrastructure, while retaining ecological values, is becoming increasingly important as coastal development proceeds (Nordstrom 2014). The affordability of bulkheads to private property owners has resulted in incremental construction of bulkhead segments that can result in a complex longshore and cross-shore configuration, including sandy beach enclaves remaining as partially sheltered remnants between bulkhead segments (Jackson et al. 2002). These beach enclaves may offer unique environmental opportunities.

One species that may use enclaves to advantage is the horseshoe crab (*Limulus polyphemus*), an important species that spawns on estuarine beaches, including locations where protective walls are common (Myers 1986; Walls et al. 2002; Botton et al. 2006). Horseshoe crabs are considered a keystone species because they depend on beaches for a portion of their life cycle, and their spawning results in delivery of eggs to shorebirds that, in turn, influences shorebird migration patterns, feeding behavior, and life cycles (Myers 1986; Castro and Myers 1993; Baker et al. 2004; Morrison et al. 2004). Horseshoe crabs also support the commercial fishing, biopharmaceutical, and ecotourism industries (Eubanks et al. 2000; Manion et al. 2000), which places a direct economic value on them.

Horseshoe crabs spawn in the greatest densities in the swash zone on foreshores at high water during spring tides. Annual surveys reveal higher density of spawning horseshoe crabs when wave heights are low (less than 0.3 m) (Smith et al. 2002). Low wave heights can occur on foreshores, even under relatively strong onshore winds, in locations where wave energy dissipation by offshore topography is relatively great or where sheltering due to

crenulated shoreline configuration offers wave refuge areas during storms (Smith et al. 2011).

Enclaves can have lower wave energies than their natural counterparts along the same shoreline reach when locally generated waves approach at an acute angle to the shoreline, because shadow zones develop on the upwind side. The lower energies in these shadow zones may increase suitability for horseshoe crab spawning relative to nearby exposed foreshores. Beach enclaves may also provide traps for eggs moving alongshore in front of bulkheads. Eggs previously buried become exhumed during spawning (Smith 2007) and during wave reworking (Jackson et al. 2014) and become available as a food source. Previous studies in Delaware Bay indicate that peak quantities of eggs moving in the swash occur during rising tide, around high tide, and on the falling tide if there is an increase in wave energy that exhumes buried eggs (Nordstrom et al. 2006; Jackson et al. 2014). Horseshoe crabs and shorebirds have been found in human-altered coastal environments, but whether they would take advantage of the beach enclaves was uncertain.

The purpose of this paper is to investigate the influence of bulkhead configuration on spawning and transport of horseshoe crab eggs to and from beach enclaves. Specific objectives are to determine (1) how the characteristics of bulkheads and enclaves and their relationship to each other compare in different developed reaches; (2) if horseshoe crabs utilize sandy enclaves for spawning; (3) if spawning in enclaves is greater during periods of high wave energies when the enclaves provide some degree of sheltering; and (4) if eggs become trapped in the enclaves, where they are made available to birds at times when the beaches in front of bulkheads are inundated. We expected the enclaves would provide wave sheltering during storm conditions and a potential sink for eggs transported in the swash.

Methods

The shoreline reaches where the study was conducted are along the eastern shore of Delaware Bay in New Jersey, USA (Fig. 1). The reaches have narrow transgressive beaches fronting marsh systems or eroding uplands. Most bulkheads are wood sheet-pile structures. The beaches have steep foreshore slopes (5°–9°) and relatively flat (<0.5°) low tide terraces. Foreshore widths are generally 25–30 m between the upper limit of swash at spring tide (non-storm wrack line) and the break in slope separating the foreshore from the low tide terrace. Tides are semi-diurnal with a mean range of 1.6–1.8 m (NOAA 2006). Prevailing winds are from the northwest, but low-pressure centers result in high-velocity northeast and southeast winds.

Fig. 1 Setting of study area, showing reaches assessed in the inventory of bulkheads and beach enclaves (*black dots*) and source of eggs used as tracers (Port Mahon)
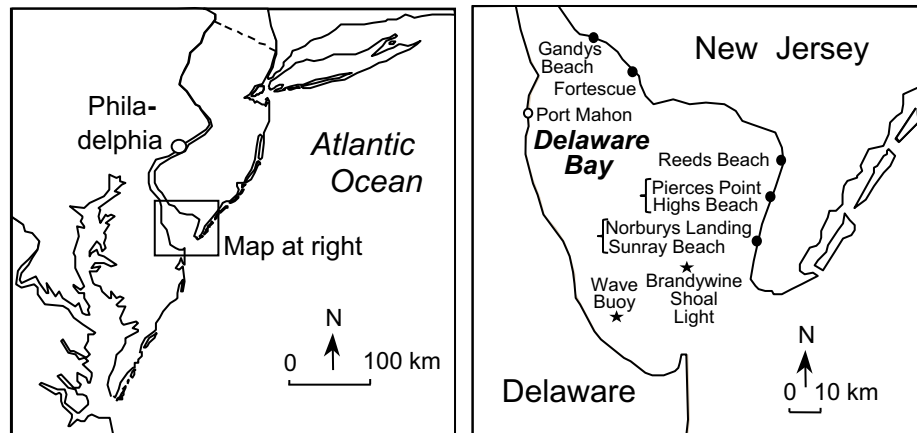
Counts of horseshoe crabs (female and male) were made in May and June 2007 on two developed reaches, Reeds Beach and Fortescue. These spawning counts were conducted at enclaves and unarmored shoreline segments during times when peak horseshoe crab spawning normally occurs but during storm conditions in the bay, when sheltering by bulkheads is expected to have its greatest relative effect. Egg tracer and trapping experiments were also conducted at one sandy enclave at each of the two sites. The experiment at Reeds Beach was designed to link the timing of egg delivery to wave, current, and tidal processes (reported in Jackson et al. 2014). The experiment evaluated here was conducted at Fortescue in June 2007 to assess the transport of horseshoe crab eggs into and out of the sheltered zone and the number of eggs that remain trapped within the enclave.

An inventory of the characteristics of bulkheads and intervening beach enclaves was then conducted in Reeds Beach and Fortescue and three other developed reaches on the eastern shore of the bay in January 2008 to place the results of the horseshoe crab counts and egg delivery studies in a broader perspective. The five reaches were selected because of the great variety of bulkhead configurations revealed on aerial photographs. Each reach was walked by two observers who measured the alongshore length of each bulkhead and enclave, and the width of active foreshore from the break in slope to the spring tidal limit (in each enclave) or to the location of intersection of the bulkhead on the active foreshore (at each structure).

Reeds Beach and Fortescue (Fig. 2) were selected for assessment of enclave use by fauna, because horseshoe crab spawning and shorebird foraging is common. Counts of horseshoe crabs and shorebirds were conducted within three representative enclaves and a nearby unarmored segment in the two reaches. The unarmored segment at Reeds Beach (Fig. 2) is 435-m long and has been heavily used by spawning horseshoe crabs and shorebirds. Accordingly, a smaller 20-m-long sub-segment was

selected for sampling. The lengths of the enclaves at Reeds Beach varied from 16 m (Enclave R3) to 60 m (Enclave R2). Enclave R1 is 32.5 m alongshore. The entire lengths of all enclaves were sampled. The unarmored segment at Fortescue is 356-m long. The sub-segment sampled was 50 m. The lengths of the enclaves sampled at Fortescue varied from 8.8 m (Enclaves F2 and F3) to 44 m (Enclave F1).

Horseshoe crab counts were conducted an hour before high tide, at high tide, and an hour after high tide. Shorebird counts were conducted on the following low tide. The number, location, and size of enclaves selected insured that sampling could be completed within a 1-h time period. Counts of horseshoe crabs on Reeds Beach were made a day before new moon on 15 May 2007, a day after new moon on 17 May, 2 days before full moon on 30 May, and the day of full moon on 01 June. Counts on Fortescue were made 2 days before new moon on 14 May, the day of new moon on 16 May, a day before full moon on 31 May, and on the day of full moon on 01 June. All counts were made on the higher of the two daily high tides, which occurred during the nighttime. Shorebird counts were made an hour before, at low tide, and an hour after low tide and were adjusted to densities per meter of shoreline for comparison. Densities of shorebirds, gulls, and horseshoe crabs inside and outside enclaves were compared using a general linear model with beach included as a blocking variable. Densities were log-transformed to better meet distributional assumptions.

Egg tracer studies were conducted in Enclave 2 at Fortescue (Figs. 2, 3) to assess flux of horseshoe crab eggs. Waves, currents, and eggs in transport were sampled over two tidal cycles on 16 and 19 June. A pressure transducer placed on the low tide terrace (Fig. 3) provided data on offshore wave characteristics and water levels throughout the 2 days. Data on wave height and current velocities on the foreshore fronting the enclave were measured with a co-located pressure transducer and bi-directional

Fig. 2 Locations of enclaves and unarmored beach segments for horseshoe crab counts for Fortescue and Reeds Beach (base map from Google Earth)

electromagnetic current meter. Data were sampled at 4 Hz continuously during trapping.

Horseshoe crab eggs laid during an earlier spawning event at Port Mahon, Delaware (Fig. 1), were dyed using food coloring. A 50/50 mixture of dyed eggs and sand excavated from the foreshore was injected into the fore-shore using cores 0.05 m in diameter and 0.15-m long placed 0.1 m apart. The number of horseshoe crab eggs relative to sand was somewhat greater than would occur under natural conditions to ensure recovery of a limited quantity of tracer from discrete locations. Three different color dyes were used to differentiate eggs injected on the two different days. Nine tracer cores were injected in two block configurations on 16 June (Fig. 3). Five cores were injected 1.5 m bayward and 1.5 m north of Transect BS (Fig. 3). Four cores of a different color tracer were placed just within the enclave to determine the likelihood for eggs to move out of the enclave and then along the beach in front of the bulkhead. On 19 June, nine cores were placed in a single block 1.5 m bayward and 1.5 m north of Transect BS. This experiment was designed to determine the likelihood for eggs moving in front of the bulkhead to enter or bypass the enclave. Tracer cores in each tracer block were exhumed at low tide and measured to determine the quantity of eggs entrained.

Numbers of eggs in transport were determined using two streamer traps. Streamer traps are hydraulically efficient

and provide reliable estimates of sediment flux in the surf and swash zones (Wang et al. 1998). The traps have a 0.1-m-wide, 0.8-m-high opening enabling sampling of the entire water column in the swash. Traps were placed at mid-swash location and oriented directly into the wave uprush. Trap deployments followed the onshore and off-shore movement of the swash along shore-perpendicular lines beginning 1-m downdrift of the tracer injection locations of Transect BS and 1 m south of Transect BN (Fig. 3). Traps were moved into the enclave when mid-swash reached the bulkheads. Trapping of five waves per deployment were made at 10-min intervals commencing when the swash uprush arrived at the tracer injection location and concluding when the swash uprush limit during falling tide was bayward of the injection location. Eggs tend to accumulate in litter lines, so the uppermost (high water) litter line was walked after the falling tide for 30 m in both directions from tracer injection locations to count tracers conspicuous on the surface.

Topography was measured at 1-m intervals within the enclave and across the foreshore at low tide before and after trapping to determine net elevation change of the beach. The tops of 10-mm-diameter steel rods driven into the sand were used as datum monuments (Fig. 3), enabling measurement of changes in elevation to within 0.5 mm. The position of the breaker line and the uprush limit was identified at 10-min intervals when egg trapping occurred.
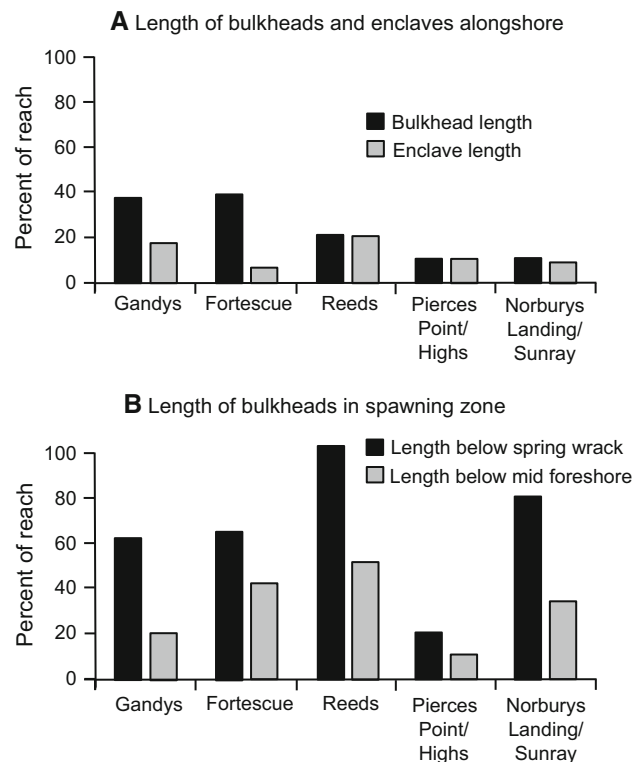
Ground view looking east
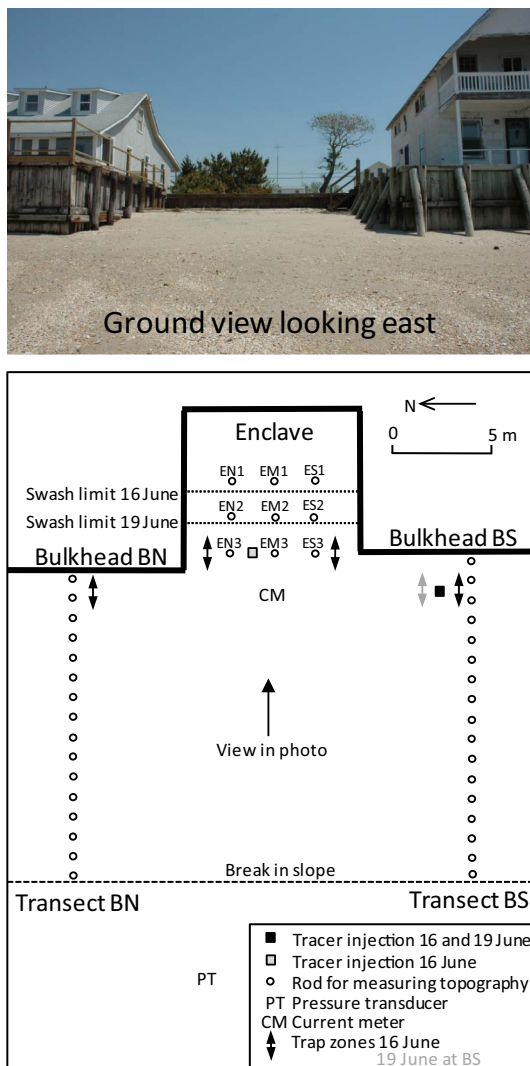
Fig. 3 Study design for egg trapping at Fortescue 16 and 19 June

Fig. 4 Inventory of bulkheads and intervening beach enclaves in the five reaches identified in Fig. 1

Results

Inventory of bulkheads and enclaves

The total length of developed shoreline in the five reaches is approximately 7.5 km. The combination of bulkhead segments and sandy beach enclaves comprises more than 40 % of shoreline length in three of the five reaches (Fig. 4a). Gandys Beach and Fortescue have shorter lengths of beach enclave compared to adjacent lengths of bulkhead segments. Equal proportions of beach enclave and bulkhead segments occur at the other three reaches. The location where the toe of the bulkhead intersects the beach profile is important for spawning horseshoe crabs that generally utilize a zone between the upper swash limit and mid-foreshore. Percent of bulkhead length intersecting below the spring wrack line ranges from 20 to 100 % at the five reaches (Fig. 4b). At least 60 % of bulkheads intersects the foreshore below the spring tide wrack elevation along four of the five reaches (Fig. 4b), thus restricting horseshoe crab spawning habitat. At Fortescue and Reeds Beach, more than 40 % of the bulkheads intersect the beach at or below the mid-foreshore (Fig. 4b), thus eliminating what would be the optimum horseshoe crab spawning locations under natural conditions. Extensive areas of undeveloped shore still exist in this portion of Delaware Bay, but the bulkheads in developed segments have fragmented the natural environments alongshore and restricted the cross-shore dimensions of the active beach. The amount of foreshore remaining below the base of the bulkheads bordering the enclaves at Reeds Beach and Fortescue, where spawning counts were made, varies from 22 to 74 % of the width of the active foreshore (between the spring tide wrack line and the break in slope) in the adjacent unarmored segments.

Horseshoe crab and shorebird counts

Wave heights in the bay were higher than typical during the horseshoe crab spawning season. Average wave heights from the offshore buoy during the period when crab counts were made ranged from 0.4-m high, 2.7 s waves on 30 May to 0.67-m high, 3.7 s on 16 May (equivalent to 0.38–0.69 m in 1-m water depth). Wave approach was

predominantly from the south/southeast at an acute angle to the shoreline. Wave heights were always greater than the 0.3-m visual wave height reported by Smith et al. (2002) when spawning decreased in Delaware Bay. Both Fortescue and Reeds Beach show similar trends in horseshoe crab densities before, during and after high tide (Table 1). The highest number of crabs is 1 h after high tide at all sites during all surveys. Crabs were frequently found clustered in the shadow zones along the south side of the beach enclaves.

Data on density of horseshoe crabs in the enclaves and unarmored sites reveal that there is a slight increase in use in the enclaves from 30 May to 1 June (Table 1). Overall, densities of horseshoe crabs did not differ significantly between sites inside and outside of enclaves ($F = 1.43$, $ndf = 1$, $ddf = 5$, $P = 0.29$) indicating that horseshoe crabs will use enclaves and areas outside of enclaves for spawning.

Use of the enclaves by shorebirds was less than at the unarmored segments at both sites (Table 2). Sand pipers and gulls used the enclaves more than other shorebirds. However, evidence suggests that both shorebirds and gulls tended to utilize sites outside of enclaves more than sites inside of enclaves ($F = 5.6$, $ndf = 1$, $ddf = 5$, $P = 0.06$ for shorebirds and $F = 6.67$, $ndf = 1$, $ddf = 5$, $P = 0.05$ for gulls).

Egg flux between the foreshore in Enclave F2 and in front of the bulkhead at Fortescue

Egg trapping on 16 June (Fig. 5) reveals limited entrainment and transport of tracer deployed in the enclave and dominance of egg transport on the foreshore during the

rising tide. Significant wave heights on the low tide terrace ranged from 0.08 to 0.12 m with periods of 2.3–2.6 s, typical of conditions during June. Mean longshore current velocities on the upper foreshore were 0.02–0.10 m s^{-1} and were directed toward the south, accounting for the greater quantity of tracer trapped at Trap Position BS.

Swash uprush during rising tide reached the tracer block fronting Bulkhead BS at 08:50. Trapping fronting Bulkheads BN and BS commenced at 9:10, shifted to the enclave from 10:40 until 11:30 and back to Bulkheads BN and BS from 11:40 until 12:30 during the falling tide. A pronounced peak in trapping occurred at 9:30 at Trap Position BS (Fig. 5) when the breakers migrated over the tracer block. Tracer from the enclave tracer block was trapped in front of Bulkhead BS during the 9:50 and 10:10 trapping periods, after the swash uprush migrated to the enclave tracer block. No tracer from the enclave tracer block was trapped when the swash zone (and trapping) shifted to the enclave.
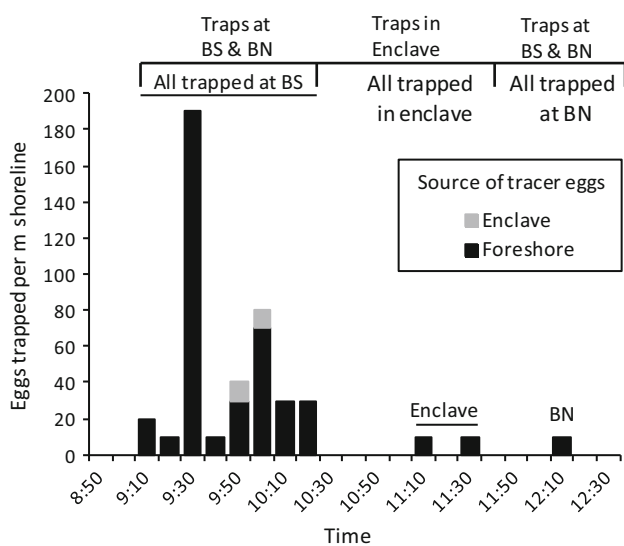
Examination of the tracer cores at low tide revealed a surface flush with the beach, indicating that the tracers were not removed from the beach at a greater rate than the sand. There was an order of magnitude difference in core length loss between the tracer block fronting Bulkhead BS (0.04-m depth) and the enclave (0.004-m depth). The landward limit of wave breaking was never landward of the enclave entrance and the onshore-directed current velocities increased the likelihood for deposition within the enclave. Net bed elevation change on the foreshore fronting Bulkhead BS revealed erosion of 0.02–0.03 m near the bulkhead and deposition of 0.01–0.04 m at distances of 6–11 m seaward of the structure. Accretion occurred across

Table 1 Density of horseshoe crabs (no. m^{-1} of shoreline) at Fortescue and Reeds Beach during high water

Fortescue						Reeds beach					
North to south	Hours to high tide	14 May	16 May	31 May	01 June	North to south	Hours to high tide	15 May	17 May	30 May	01 June
Enclave F1	−1	0.0	0.0	1.3	1.6	Unarmored	−1	1.1	1.0	0.2	0.8
	0	0.0	0.1	1.8	2.1		0	2.9	0.8	0.2	1.0
	+1	0.1	0.2	1.4	2.4		+1	4.3	1.4	0.7	2.4
Enclave F2	−1	0.0	0.0	0.0	0.2	Enclave R1	−1	0.5	0.3	0.4	1.7
	0	0.0	0.0	0.2	0.1		0	2.7	1.4	1.0	2.2
	+1	0.5	0.1	0.5	0.1		+1	3.5	1.9	1.8	2.5
Enclave F3	−1	0.0	0.1	0.9	1.4	Enclave R2	−1	2.2	0.4	0.8	2.4
	0	0.0	0.1	2.2	2.0		0	2.7	0.7	2.4	2.5
	+1	0.3	0.1	2.8	4.9		+1	2.8	0.7	3.5	3.6
Unarmored	−1	0.0	0.2	0.3	0.2	Enclave R3	−1	1.0	0.2	0.3	1.7
	0	0.1	0.2	0.5	0.2		0	3.3	0.2	0.7	2.4
	+1	0.7	0.1	1.5	1.1		+1	2.4	0.3	2.5	2.9
Mean$_{Enclaves}$		0.1	0.1	1.2	1.6			2.3	0.7	1.5	2.4
Mean$_{Unarmored}$		0.3	0.2	0.8	0.5			2.8	1.1	0.4	1.1

Table 2 Density of shorebirds (no. m^{-1} of shoreline) at Fortescue and Reeds Beach during low water

|	North to south	Semipalmated sand piper *Calidris pusilla*	Red knot *Calidris canutusrufa*	Ruddy turnstone *Arenaria interpres*	Sanderling *Calidris alba*	Laughing gull *Leucophaeus atricilla*	Herring gull *Larus argentatus*	Common grackel *Quiscalus quiscula*
Fortescue	Enclave F1	0.2	0.0	0.3	0.0	0.1	0.3	0.9
	Enclave F2	0.0	0.0	0.0	0.0	0.2	0.0	0.0
	Enclave F3	0.1	0.0	0.1	0.1	1.7	0.0	0.6
	Unarmored	0.2	0.0	0.1	0.0	3.9	0.3	0.1
Reeds beach	Unarmored	0.2	8.8	18.0	10.0	22.1	1.0	0.2
	Enclave R1	0.0	0.0	2.2	0.7	10.1	0.3	0.1
	Enclave R2	1.6	0.0	0.2	0.0	4.0	0.0	0.1
	Enclave R3	2.7	0.0	0.1	0.0	0.8	0.0	0.0

Fig. 5 Eggs trapped on 16 June within the Enclave (*E*), and fronting the bulkhead to the north (*BN*) and south (*BS*). *Shading* indicates eggs originating from cores on the foreshore fronting the enclave (*Black*) or within the enclave (*Gray*)

the upper foreshore in the enclave (Fig. 6), with less accretion on the north (updrift) side. Accretion of 0.03 m in the enclave at EM3 (Fig. 3) would inhibit entrainment of the enclave tracer by the shallow swash, resulting in no tracer trapped after 10:00 (Fig. 5). Few tracer eggs (about 2 per m of shoreline) were stranded in the litter line at Bulkhead BS, and all were from the tracer block fronting that bulkhead. A total of only two eggs from the tracer placed in the enclave were found in the entire litter line in the enclave, reflecting the limited amount of tracer exhumed.

Egg trapping on 19 June demonstrates how the enclave can serve as a trap for eggs entrained and transported from the foreshore fronting an updrift bulkhead. Wave heights on the low tide terrace (Fig. 3) ranged from 0.09 to 0.15 m with wave periods of 2.5–3.0 s. Longshore current

velocities on the upper foreshore were directed to the north with means of 0.06–0.24 m s^{-1}. Cross-shore velocities were directed onshore for the duration of egg trapping. Trapping occurred between 11:52, when the tracer block fronting Bulkhead BS came under the influence of the swash, and 15:25 when the swash limit migrated bayward of the injection site. The largest peak in tracer trapped (Fig. 7) occurred at 12:02 fronting Bulkhead BN when the swash was reworking the tracer block fronting Bulkhead BS. The peak in tracer counts in the landward migrating litter line in the enclave (Fig. 8) also occurred about this time (12:15). The upper limit of swash uprush was located in the enclave, 1.5 m landward of Bulkhead BS. The lack of tracer in the traps between 12:22 and 13:12 is a result of the previous mining of available tracer by beach erosion in the swash. A second smaller peak in tracer (13:22–13:32) occurs when waves break directly on the tracer block. The tracer was conspicuous in the litter accumulating at the swash uprush limit in the enclave during all sampling periods (Fig. 8). The peak in tracer there coincided with the peak in the tracer counts fronting Bulkhead BN, indicating rapid dispersion of exhumed eggs. The tracer was found in the enclave during times when no tracer was trapped in front of the two adjacent bulkheads (e.g., after 12:12 and
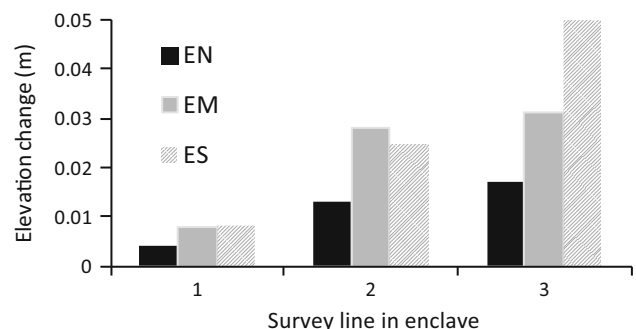
Fig. 6 Net bed elevation change in the enclave on 16 June. Locations are identified in Fig. 3
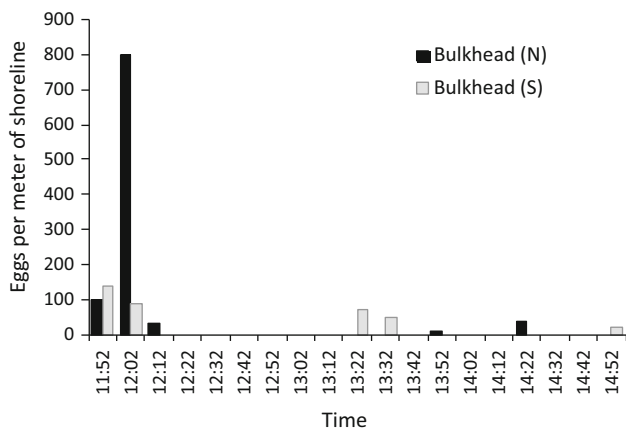
Fig. 7 Number of eggs trapped at Bulkheads BN and BS on 19 June
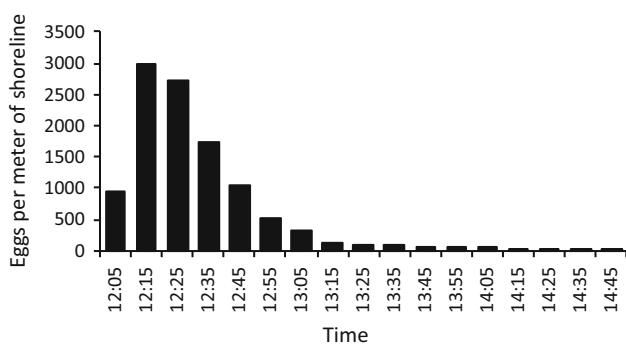
Fig. 8 Number of eggs stranded in the litter line at the swash uprush limit in the enclave 19 June

before 13:22) when the breakers migrated over the tracer core block fronting Bulkhead BS. Bulkhead BN intersects the foreshore 0.85 m bayward of Bulkhead BS, providing a trap for eggs moved alongshore by the longshore current and onshore by swash uprush velocities within the enclave.

Net changes in topography revealed erosion of just over 0.06 m within 1.5 m of Bulkhead BS and 2 m of Bulkhead BN and a small zone of deposition (10 mm) at Transect BS just bayward of the location of the tracer core block (1.5 m). Averaged core tracer depth exhumed during the tidal cycle was 0.03 m. Most of the tracer was exhumed at 12:02 (Fig. 7), accounting for the low quantity of tracer released and subsequently recovered by trapping at other times.

Discussion

The results of this study indicate that combinations of bulkheads and sandy beach enclaves are common on the five reaches on the eastern shore of Delaware Bay (Fig. 4a) and that many of the bulkheads reduce horseshoe crab spawning habitat by extending below mid-foreshore

(Fig. 4b). Extensive areas of undeveloped shore still exist, but the presence of beach enclaves within segments of bulkhead provide local refuges for spawning and food sources.

Historical spawning counts at Fortescue reveal a decrease in spawning densities in 2007 compared to previous years, with an estimated 67 % decline in 2007 compared to 2006 (Swan et al. 2007). The lower rates in 2007 are attributed to the high wave conditions in the bay when horseshoe crab spawning densities should be at a maximum. Our results show that horseshoe crabs utilized sandy beach enclaves between bulkhead segments for spawning when weather conditions were unfavorable. Spawning densities were greater in enclaves than on longer unarmored segments on some days, providing some evidence of increased spawning due to sheltering by adjacent bulkheads.

The clustering of spawning horseshoe crabs in enclaves may be attributed to (1) the sheltering (refuge) from waves interacting with the bulkheads; (2) crabs being passively moved into the enclave by the swash as they pass along the front of the adjacent bulkheads; or (3) the trapping of crabs already in the enclave by the longshore obstructions provided by the bulkheads. Vertical structures that extend out onto the intertidal zone can create areas of low wave energy and decreased current velocities near the structure. Bowman and Dolan (1985) observed greater densities of common mole crabs, (*Emerita talpoida*) along a pier on a sandy beach when dominant waves approached the structure at an angle, creating low wave energy shadow zones. Knox and Boolootian (1963) also observed greater densities of the sand crab (*Emerita analoga*) on a section of beach sheltered by a series of piers.

The spawning that occurred under wave conditions less than optimal (>0.3 m) (Smith et al. 2002) and the slight increase in use when waves approached from the southerly quadrants provide some indication of the importance of sheltering. Structures built perpendicular to the shore can serve as traps for eggs transported alongshore in the swash zone and provide concentrated food sources for foraging birds (Botton et al. 1994). Results of the tracer experiments support earlier findings that quantities of eggs moving in the uprush are greatest during rising tide and around high tide, related to the exhumation of eggs by the migration of swash and breakers (Nordstrom et al. 2006; Jackson et al. 2014). Beach enclaves between bulkheads provide a sink for eggs moving along the base of the bulkhead, where there is no mechanism for accumulation of eggs.

Shorebird foraging behavior has been tied to the integration of food availability, habitat type, and interaction with other species (Karpanty et al. 2006; Pomeroy 2006; Burger et al. 2007). Shorebird distribution is associated with natural shoreline discontinuities that trap and increase

availability of horseshoe crab eggs (Mizrahi and Peters 2009). Shorebird foraging behavior is a result of the trade-offs between energy intake and perceived risk of mortality (Pomeroy 2006). Given these factors, there are a few potential explanations for the lack of shorebirds in the enclaves. The elevation of the bulkheads that define the boundary of the enclaves decreases the likelihood that shorebirds can avoid predators. The proximity of the enclaves to human development increases the likelihood for disturbance from people, cars, and dogs. These factors, and the presence of larger birds (i.e., gulls), can discourage use by most shorebirds (i.e., red knots) (Burger et al. 2007) and account for the lack of shorebirds in the enclaves.

Any advantage that accrues as a result of enclaves between bulkheads serving as traps for eggs moving alongshore is overridden by the disruption of the adjacent bulkheads to natural processes and habitats, especially when those bulkheads intersect below mid-foreshore. The enclaves are created near locations of human habitation, which increases the probability of disturbances to shore-birds, while the bulkheads break up the natural corridors of longshore transport of sediments and biota between adjacent natural areas. Retaining natural enclaves between bulkheads cannot totally replace the lost natural values, but provides some advantages over completely armoring the shore.

Conclusions

Enclaves can serve as sinks for eggs moving along the base of a bulkhead. Despite these localized advantages, most birds feeding on horseshoe crab eggs prefer sites outside the enclaves. Nevertheless, having unarmored enclaves between bulkhead segments may be preferable to one continuous bulkhead, based on environmental benefits.

The many studies of the effects of shore-parallel walls on cross-shore exchanges of sediment and biota should be supplemented by studies of longshore exchanges and the influence of bulkhead construction on these exchanges. Development of shore protection plans is often done on a reach basis, but this does not mean that building a single linear structure is the optimum strategy. Incremental construction may be considered as a planned strategy to help preserve natural refuge areas rather than a haphazard response to site-specific shore protection needs. Where a longer reach requires protection, structures can be set back farther from the water in locations where infrastructure is less threatened, thereby conserving beach space for a longer time.

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