Beach Nourishment on Delaware Bay Beaches to Restore Habitat for Horseshoe Crab Spawning and Shorebird Foraging

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INTRODUCTION

This study was motivated by the recognition that beach nourishment can influence the suitability of a particular beach for horseshoe crab spawning. This was recently illustrated by a beach nourishment project at North Bowers Beach, which had been nourished previously in 1998 using sediment from an offshore shoal that converted a previously narrow coarse sand/gravel beach to a wider, medium to fine grain sand beach. Spawning counts at North Bowers were high immediately following the nourishment; however, recent years revealed a dramatic drop in spawning on the beach that has not been observed at neighboring beaches and that has been attributed to the fining of foreshore sediments. Accordingly a pilot project was designed to nourish a portion of the intertidal foreshore with coarser sediments and monitor the changes to horseshoe crab spawning activity and factors that are likely to affect horseshoe crab spawning.

Beach nourishment is a widespread practice for shoreline protection, but projects that use beach nourishment to create a veneer of sediment to improve habitat are rare. In addition to adding coarse sediments to the previously nourished North Bowers Beach, half of Pickering Beach was restored in late 2001 using coarse sediment as its initial treatment. This study was designed to take advantage of previously planned nourishment at Pickering Beach to expand the objectives and examine the response of horseshoe crabs at multiple beaches: two that had been recently nourished (since 2001) and two that had been previously nourished (no later than 1998).

The report begins with a review of the relationship between sediment, water flow, and horseshoe crab spawning. We then present study methods and results. We conclude the report with a discussion of and recommendations for beach nourishment where horseshoe crab spawning is an objective or a constraint on the restoration project.

REVIEW OF THE RELATIONSHIP BETWEEN HORSESHOE CRAB SPAWNING AND BEACH HABITAT

Horseshoe crab ecology and management in Delaware Bay

Delaware Bay is an estuary of extraordinary biological value. The bay provides important habitat to migratory shorebirds and has been identified as a primary “staging area” along the Atlantic Coast. Up to one million shorebirds utilize the littoral resources of the estuary during spring migration (Botton et al. 1994). In addition, Delaware Bay provides habitat to the world’s largest population of spawning horseshoe crabs. The arrival of migratory shorebirds coincides with the peak of horseshoe crab spawning activity in May. Hungry birds arriving from the Caribbean and South America feast upon abundant horseshoe crab eggs exposed on bay beaches, fueling up for their flight to summer breeding grounds in the Arctic. The National Audubon Society and the American Bird Conservancy have recently designated the Delaware Bay coast as a globally important bird area.

The recent horseshoe crab harvest restrictions promulgated by the Atlantic States Marine Fisheries Commission have brought the issue of potentially declining horseshoe crab populations to the forefront of the public’s attention. There is significant debate over whether the recent restrictions will sustain the fishery. As important as these restrictions are for sustaining horseshoe crabs and shorebirds, this singular focus may be diverting attention from other critical issues such as habitat loss and change. Without adequate high quality habitat to support these species, harvest restrictions will be nothing more than short-term stopgaps that delay inevitable population level problems for these internationally important species.

History of beach nourishment in Delaware Bay

Delaware Bay is a place of dynamic change with much of the shoreline's ecological value resulting from its interaction with sea and wind. Natural change is constrained and at times exacerbated by man-made developments. This results in beach habitats being squeezed between small coastal communities and the bay, loss of beach habitat to rising sea levels, and impacts on beach geomorphology due to increasing "storminess" associated with climate change. Consequently, natural coastal habitats used by horseshoe crabs and migratory shorebirds are eroding away and changing with potential long-term implications to the conservation of beach-dependent species. As a result, there is an urgent need to conserve, restore, and enhance intertidal beach habitat to benefit biodiversity and people as an integral part of long-established coastal hazard reduction strategies for Delaware Bay, which had been motivated previously by protection of coastal communities.

In Delaware Bay storm damage and longshore transport greatly affect beach characteristics. Each year, Delaware Bay beaches erode between 2 and 6 meters per year (Galofre, 2002). Severe erosion due to storms can result in loss or damage to property, interruptions in the transportation network and loss or damage of both littoral habitat and adjacent wetlands. In recognition of the need to conserve, restore, and enhance public and private beaches, and to insure their use as protective and recreational lands the State of Delaware passed its Beach Preservation Act (Chapter 68, Title 7 of the Delaware Code) in 1972. The Beach Preservation Act empowers the state to prevent damaging alterations to the protective primary dune line, to prevent beach erosion, and to make certain destructive acts to beaches punishable as crimes. The act gives the state jurisdiction over use of private as well as public property. During the same time period, the State implemented its own dredging program and purchased dredges to address the navigational needs of recreational boaters in Delaware's Inland Bays. These dredges are also used now for major Bay-front nourishment projects. The DNREC Division of Soil and Water now implement both programs.

Delaware Bay beaches have been regularly nourished since 1962. Approximately 3 million cubic yards of sand have been placed on Delaware Bay beaches in Delaware over the past 40 years. These projects have been designed to eliminate the use of hard structures such as bulkheads and to protect coastal communities from storm damage, but have not historically included specific considerations for the restoration of littoral habitat.

Although beach nourishment is likely to preserve habitat value better than some alternative shoreline protection methods, such as bulkheading, the result of nourishment can enhance, preserve, or decrease habitat value depending on beach geometry and sediment matrix. Because of the widespread application of nourishment, the possibility of decreasing habitat value is of particular concern.

Relationship between sediment characteristics, water flow, and horseshoe crab spawning

Movement of water through the beach matrix with the rise and fall of the tide affects use of the foreshore and viability of species by influencing erosion and deposition and flushing of oxygen and organic material (McLachlan and Turner, 1994). The movement of the water table over the tidal cycle is influenced by physical parameters (beach geometry, sediment size, sorting and porosity), tidal elevation, and wave action.

The amount of water infiltrating into the beach is dependent on the permeability or hydraulic conductivity of the foreshore sediments. The permeability of the foreshore increases with grain size and, to a lesser extent, sediment sorting (Krumbein and Monk, 1949). The moisture content of the sediments in the unsaturated zone above the water table will play a role in controlling viability and egg development. The phreatic surface (water table) is the surface where pore-pressures are equal to atmospheric pressure. The vadose zone is the moist region above the phreatic surface or water table. In this zone the pore-pressures are less than atmospheric pressure due to capillarity (surface tension + molecular attraction). In this zone moisture characteristics will vary with decreasing moisture content with increasing distance above the water table. Immediately above the phreatic surface is a zone of saturation called the capillary fringe where pore-pressures are negative (Nielsen and Perrochet, 2000). An approximation of the thickness of the capillary fringe (*B*) can be estimated by (Turner and Neilsen 1997):

$$B = \frac{10\sigma}{\rho g \overline{D}}$$

where *B* is the thickness of the capillary fringe, σ is the surface tension of the fluid (0.074 N/m), ρ is the density of the fluid (1009 kg/m^3), *g* is the acceleration of gravity (9.81 m s^2), and $\overline{D}$ is the grain diameter.

The width of the capillary fringe is a function of sediment size; the width increases with decreasing grain size (McLachlan and Turner, 1994). Coarse sands and gravel facilitate downward water movement and contribute to rapid drainage of the water table. Medium to coarse sands are the dominant fraction on many sandy estuarine barriers in the mid to upper foreshore, and so drainage is facilitated on these beaches.

Shuster (1982) suggests that horseshoe crab egg viability depends on temperature, moisture and oxygen gradients across the foreshore. Penn and Brockman (1994) found that horseshoe crab egg development was lower on the lower foreshore (sublittoral zone) where saturated sediments and lower interstitial oxygen reduced development and on the upper foreshore (supralittoral zone) where low moisture caused eggs to desiccate. Egg development is maximized on the mid-foreshore where the sand remains damp, and where most horseshoe crab eggs are found. Differences in the form and mobility of estuarine beaches and their drainage characteristics can occur with differences in grain size characteristics, and artificial beach nourishment operations that introduce different kinds of beach sediments may alter the suitability of nourished beaches as habitat. Finer grain size of fill sediment can lead to a flatter foreshore slope, burial of surface gravel, and burial of the inner low tide terrace in the erosional phase of storm cycles (Figure 1).

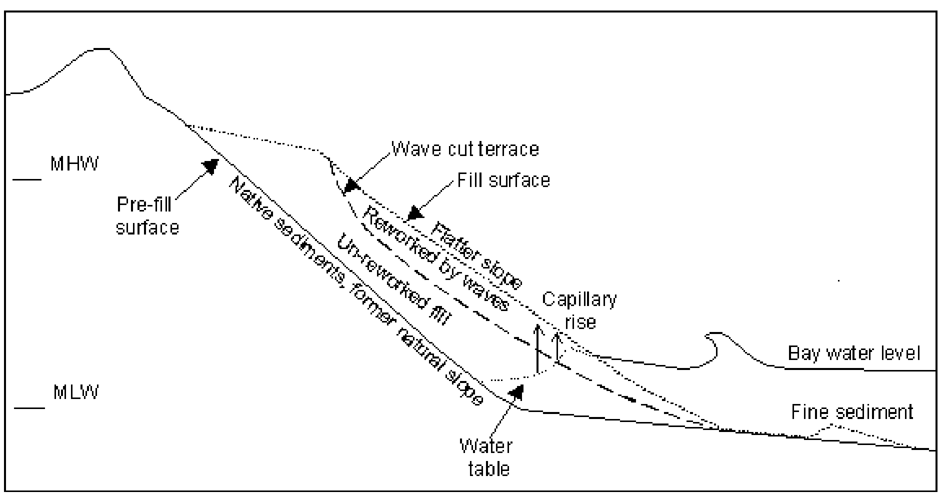

Figure 1. Conceptual diagram of estuarine beach nourished with finer sediment and reworked by waves.

The location and design of beach nourishment projects are typically driven by human benefits, such as protection of property from storm damage and suitability for human recreation. A wider, flatter beach with well-sorted sand and lack of surface gravel is more attractive for recreation, but designing an estuarine beach towards these criteria may have negative biological impacts. Finer-grained sediments used in beach nourishment operations are problematic because they increase turbidity levels during placement, but these sediments also will affect biota and the structure of habitats after they settle and become part of the beach matrix. A significant proportion of fine-grained materials in beach fill will affect moisture-retention characteristics and, if they settle as layers, may create substrate more resistant to waves and burrowing by organisms because a sediment bed with low porosity and high density will behave as solids. The hydraulic conductivity in the beach may decrease, causing lower rates of water table discharge and potentially higher rates of capillary rise.

Fill sediments that are too fine to occupy the active wave and swash zone are removed from the foreshore. Data from unnourished beaches located in Delaware Bay indicated that sediments finer than about 0.063 mm are uncommon on the foreshore but are present in the detached bars on the low tide terrace. Fill sediments remaining on the foreshore will be reworked in the active layer and will become similar to native beach materials. However, the depth of reworking of sediment by estuarine waves is limited, resulting in a wave-cut contact in fill deposits (Figure 1), leaving an undisturbed layer of fill that may be closer to the surface than the depth reached by burrowing organisms. Data from Delaware Bay indicate that the depth that horseshoe crabs deposit their eggs may be greater than the active layer on an eroding nourished beach.

METHODS

Study design

Overall the study was designed to compare horseshoe crab spawning before and after beach nourishment. Two of the study beaches were subject to recent nourishment and another two beaches, which had not been nourished since 1998, served as controls. The nourished beaches were North Bowers and Pickering. Kitts Hummock and Ted Harvey beaches served as controls. Kitts Hummock had been nourished most recently in 1996 with 32,850 CY deposited by dredge (DNREC). Ted Harvey had been nourished in 1995-1996 with 50,000 CY and in 1998 with 3,000 CY (DNREC).

Surveys of spawning and egg density in 2001 and 2002 provided data on spawning activity prior to and after nourishment. Measurements of physical processes were taken at two sites on one nourished beach (North Bowers) to provide an understanding of geomorphology and hydrology. Because reproductive potential and fitness are the underlying mechanisms for habitat selection, egg viability and development were studied at one nourished (North Bowers) and one control (Ted Harvey) beach. Methods used by Penn and Brockmann (1994) to study egg development were adapted for this study.

Nourishment at North Bowers

North Bowers Beach is located in Kent County Delaware, between the St. Jones and Murderkill Rivers. An incorporated community is located here, with homes and fishing-related businesses extending the entire length of the shoreline.

The Delaware Department of Natural Resources and Environmental Control (DNREC) first replenished the beach at North Bowers with a hydraulic dredge in 1973-

74 to protect against erosion and loss of property. Approximately 44,600 cubic yards of material was placed during this initial project. Two nylon Dura-Bag groins were placed at the north and south ends to retain the beach fill. The south groin, located at the Murderkill River, is approximately 250 meters long, the north groin, located at the northern extent of the town south of the St. Jones River, is approximately 130 meters long (Galofre, 2002). Since the initial project construction, North Bowers Beach has been periodically replenished by DNREC, primarily using a hydraulic dredge. Large-scale projects occurred in 1988 and 1998, where 51,700 and 101,400 cubic yards of material was placed, respectively.

Placement of coarse-grained sediment at North Bowers Beach occurred between April 9-11, 2001. Beach access for the construction equipment was coordinated with the Mayor of North Bowers Beach, Frenchy Poulin. Fences and signposts at the entrance the beach were removed by DNREC Division of Soil and Water staff and replaced after project completion. Sediment was obtained from Tilcon Delaware, Inc. and hauled by truck to North Bowers Beach by private contractors. The Division of Soil and Water Conservation dispatched two front-end loaders (and equipment operators) to place the sediment in the appropriate areas on the beach. A total of 921.15 tons (614.10 cubic yards) of coarse sand was placed on two separate 300 linear foot treatment areas from the low tide shelf to the storm tide line (Figure 2). The coarse sand was top-dressed with 190.68 tons of pea gravel (127.12 cubic yards). In order to increase the volume of pea gravel in the spawning area, it was placed only between the low tide terrace and the high water mark. The total depth of coarse sand and pea gravel in the replenished areas varied from 10-20 centimeters.

The DNREC Division of Soil and Water Conservation/Delaware Coastal Programs obtained all required permits and permissions for this project. Permits for placement of sediment were obtained from the Department of the Army, Corps of Engineers (CENAP-OP-R-200200218-15) and DNREC Division of Water Resources, Wetlands and Subaqueous Lands Section (WQC-026/02).

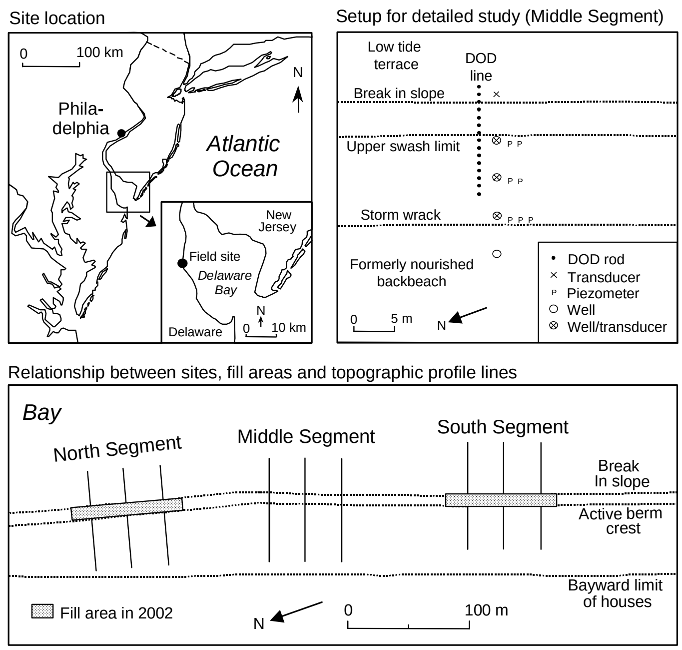

Figure 2. Field site and study design at North Bowers Beach.

Nourishment at Pickering

Pickering Beach is located in Kent County, Delaware, east of Dover and the Dover Air Force Base. A small community is located there, with houses along only one road that parallels the shoreline. The DNREC initially replenished Pickering Beach in 1978 with 85,200 cubic yards of material. It was replenished again in 1990 with 55,400 cubic yards of material and in 2001/2002 with 37,500 cubic yards of material (Galofre, 2002).

During 2001, dredged sediment was pumped onto Pickering beach via hydraulic dredge by DNREC. The north portion (approximately half) of the beach was nourished prior to horseshoe crab spawning in 2001. The remaining south portion was nourished later in 2001. Our study sections were located in the south portion so that we observed spawning prior to (2001) and after (2002) nourishment. Sediment placed was medium to coarse sand, similar in composition to the beach at that time, and thought to be optimum for horseshoe crab spawning. Sediment size distribution of nourished sand was not available at the time of this report.

Nourishment Ted Harvey

The beach and dune at Ted Harvey Wildlife Area is the primary protection for State-owned and managed coastal wetland impoundment structures. These types of impoundments were first constructed in the 1950's and 60's for the purpose of waterfowl hunting and mosquito control. Since then, these structures have been upgraded and retrofitted so that tidal exchange can occur, resulting in improved water quality and use for estuarine fishes and invertebrates and for wading birds and shorebirds.

In 1995-96, approximately 50,000 cubic yards of material was placed by hydraulic dredge for the primary purpose of protecting the impoundment from erosion and to maintain habitat and water quality values. Dunes were constructed as part of this project. In 1998, 3,000 cubic yards of material were placed on the beach.

Nourishment at Kitts Hummock

Kitts Hummock Beach is located in Kent County, Delaware, east of Dover and the Dover Air Force Base. A small community of both permanent and summer residents is located along the community's one road, which parallels the shoreline.

The DNREC initially replenished Kitts Hummock Beach in 1974 with 46,500 cubic yards of material for the primary purpose of storm protection. Subsequent major projects were conducted in 1979, 1988 and 1996 with 74,000 cubic yards, 15,780 cubic yards and 32,850 cubic yards of material respectively.

Spawning surveys

Project staff and volunteers conducted spawning surveys at Ted Harvey Wildlife Area Beach, Bowers Beach, Kitts Hummock, and Pickering Beach. Volunteers contributed a total of 144 hours to the spawning surveys. Beaches were monitored on twelve dates that coincided with the new and full moons in May and June. Spawning survey methods, which were described in Smith et al. (2002), were implemented in 2001 and 2002 at the four beaches except for Ted Harvey beach in 2001. At Ted Harvey in 2001 spawning horseshoe crabs were counted within four randomly placed 1 m by 50 m strips selected along 1 km of beach. The survey nights were the same for all beaches in 2001 and 2002.

Egg surveys

During the last weeks of May (29 and 30 May) and June (26 and 27 June), cores of sediment were collected from multiple beach segments at North Bowers, Ted Harvey, and Pickering for the purpose of estimating the density of horseshoe crab eggs. Cores were taken at 5 m intervals along shore and 1 m intervals across shore. Cores of sediment were pooled within beach elevation strata to study distribution of eggs across the foreshore. Individual cores were separated into 0 to 5 cm and 5 to 20 cm depths because 0 to 5 cm represents the horseshoe crab eggs potentially available for shorebird consumption and 20 cm is considered to be near the maximum depth that horseshoe crab eggs are laid. Permits for collection of horseshoe crab eggs was obtained from the DNREC Division of Fish and Wildlife Fisheries Section.

Eggs were separated from sand using methods developed by coauthor Dr. Richard Weber. Pooled core samples were flushed through a series of screens to separate eggs from most of the beach sediments (6.4 mm, 3.2 mm and 1 – 1.5mm). The eggs and some beach substrate were retained on the final screen, of mesh size 1mm – 1.5 mm. Eggs were separated from the sediment by elutriation with running tap water. Eggs and residual peat at this stage were frozen until further separation and quantification.

Samples were thawed and peat and microfaunal particles were hand picked from each sample using tweezers. A 10% solution of $MgSO_4$ and tap water was used to separate unembroynated eggs from embroynated eggs. Embroynated eggs were discarded. Direct counts of eggs were made when samples were small. Volumetric measurements were made when samples were too large to be hand counted.

Analysis of spawning activity

We conducted an ANOVA to estimate the difference in spawning activity at beaches that were recently nourished (North Bowers and Pickering were nourished in 2001 and 2002) versus beaches that were previously nourished (Ted Harvey and Kitts Hummock were most recently nourished in 1998). We measured spawning activity as both the density of spawning females and the density of eggs. Least square means were computed along with 90% confidence intervals to estimate spawning activity and to contrast spawning activity between beaches.

Beach and sediment characteristics at North Bowers

Topographic profiles were taken at North Bowers prior to fill emplacement (6 April) and just after fill emplacement (12 April) and before and after a detailed process-based investigation of the characteristics of waves, water table, and interstitial moisture (15 and 16 May). Topographic surveys, using a rod and transit, extended from the backbeach or dune well above the limit of wave attack out onto the low tide terrace along three shoreline-perpendicular lines in three segments, representing the two 90 m long fill areas and an untreated beach between them (Figure 2).

Visual observations were made of the sediment characteristics on the beach surface and in shallow pits (0.30 m deep) on the upper, mid and lower foreshore on the middle line in each of the three beach segments on 6 and 12 April. Sediments were gathered on the center profile of the Middle and South Segments (Figure 2), on 15 and 16 May, when beach processes were measured. The samples were taken in pits at 0.15 m increments between the beach surface and the water table elevation at low tide. The number of samples taken each time varied according to the elevation of the water table and ranged from a maximum of 5 at 45 m on the Middle Segment when the water table was low to a minimum of 1 at 50 m on the Middle Segment when lower elevations were inundated at high stages of the tide. Sediments were washed, dried, and sieved at 0.5 phi intervals. Mean and sorting of sediments were calculated using inclusive graphic measures (Folk 1974).

Bulk sediment samples were taken at 0.17 m depth on the Middle and South Segments on 15 and 16 May at the three locations on the foreshore profile where egg pouches were buried to evaluate moisture characteristics. The depth was chosen because it is the depth that egg pouches were buried. Samples were taken every 45 min and were analyzed for moisture characteristics by first sealing samples in air-tight plastic bags and weighing them, followed by air drying and re-weighing.

Net change of the sand surface elevation and depth of sediment activation across the foreshore was determined using rods driven into the sand at 1 m intervals cross-shore from the location of spring tide to the break in slope. A loose fitting washer was placed over the rods to measure depth of activity of sediments according to the procedure identified in Greenwood and Hale (1980).

Process measurements were taken along the middle cross-shore transect in a portion of the beach that was not nourished in 2002 (Middle Segment) and along the middle cross-shore transect in one of the newly nourished segments (South Segment). Elevation of the beach water table was obtained from three pressure transducers installed in 41.0 mm internal diameter commercial well points located on the intertidal foreshore. The three elevations were selected to correspond to locations of egg pouches designed to evaluate egg viability (see next section). The water table was measured manually in a fourth well point located above the intertidal beach. Bay water levels were measured with a pressure transducer located on the low tide terrace. At least two piezometers were installed adjacent to the lower three well points to estimate the hydraulic conductivity and direction of flow. The piezometers consisted of 50.8 mm diameter pvc tubing with the lower end encased in fine-mesh filter cloth. Data from all four pressure transducers were gathered at 1 Hz over the tidal cycle at the two segments.

Egg transplant and development

During early May, newly laid horseshoe crab eggs were extracted from an approximately 10 m x 10 m area of the beach at Port Mahon and transplanted to North Bowers and Ted Harvey. Selection of eggs for transplanting was based on formation of well defined and firm clusters, absence of egg swelling, and egg coloration of light green or light blue. All clusters had some visible gravel. Clusters of eggs weighing approximately 50 gm were placed into sixty mesh pouches (15 cm x 15 cm) and buried to a depth of 15 to 20 cm into the foreshore at three elevations: 0.8, 0.5, and 0.2 of foreshore width. Each pouch was tied to the center of an 11 cm diameter plastic disc, which was buried 20 to 30 cm below the pouch to serve as an anchor and prevent vertical movement of the pouches. Eggs were excavated on 2 and 3 May and 9 and 10 May. Twenty-four pouches were transplanted at North Bowers and 12 at Ted Harvey during each of the two time periods. The bearings and distances from landmarks on the back beach were taken so that pouches could be located.

Pouches remained in place for 30 to 40 days prior to removal. Pouches were placed in buckets of wet sand and transported to Delaware National Estuarine Research Reserve (DNERR) where eggs were removed from pouches and preserved in 10% buffered formalin. In the lab at USGS LSC-AEL, Kearneysville, WV, eggs were separated from sand and the eggs' stage was identified under magnification. We floated eggs in a solution of 10% epsom salts to separate viable eggs, which sank, from dead eggs, embryos, and triolobite larvae, which floated. All stages lacking jointed legs were considered eggs (cf. Sekiguchi (1988) Stage 17 and earlier). Embryos had jointed legs, but were surrounded by membranous tissue (chorion or inner membrane) (cf. Sekiguchi

(1988) Stages 18 to 21). Larvae had shed their chorion and inner membrane (cf. Sekiguchi (1988) Stage 21b and older). Color of eggs was recorded. Presence of macrofauna was noted and identified. Permits for collection of horseshoe crab eggs was obtained from the DNREC Division of Fish and Wildlife Fisheries Section.

RESULTS

Spawning activity

In 2001, density of spawning females at North Bowers was the lowest among the four beaches included in this study (Table 1). In 2002, spawning at North Bowers was still the lowest among the four beaches; however, North Bowers was the only beach that showed an appreciable increase in spawning from 2001 to 2002. At Pickering, spawning remained constant from 2001 to 2002. At Ted Harvey and Kitts Hummock, spawning decreased from 2001 to 2002.

Between-year changes in spawning activity showed month-specific (Figure 3). Spawning had declined, on average, from May 2001 to May 2002 at Ted Harvey and Kitts Hummock (the control beaches in Figure 3). In contrast, spawning had increased, on average, from May 2001 to May 2002 at North Bowers and Pickering (the nourished beaches in Figure 3). Spawning declined, on average, from June 2001 to June 2002 for all four beaches, but declined most dramatically for Ted Harvey and Kitts Hummock.

Table 1. Density of spawning females (ISA = no. of spawning females per m^2).

Beach	Most recent nourishments	Quantity (cubic yards)	2001		2002	
			ISA	SE	ISA	SE
North Bowers	1998	101,400	1.04	0.0835	1.20	0.0581
	Pre-spawning in 2002	800				
Pickering	1990	55,400	1.62	0.2718	1.68	0.1286
	Pre- and post-spawning in 2001	37,500				
Ted Harvey	1996	50,000	2.63	0.4262	1.35	0.1951
	1998	3,000				
Kitts Hummock	1996	32,850	2.35	0.6702	1.36	0.2256

Egg density

Egg sampling was not conducted on Kitts Hummock in 2002. Results are presented for North Bowers, Ted Harvey, and Pickering.

For May samples, egg densities were higher in 2002 than in 2001 among the three beaches (Table 2 and Figure 4). Egg density increase exceeded 200% at North Bowers, 20% at Ted Harvey, and 380% at Pickering. However, for June samples there was a substantial drop from 2001 to 2002 among the three beaches. The increase in egg density from May 2001 to May 2002 was greater, on average, for nourished beaches (North Bowers and Pickering) compared to Ted Harvey, the control beach (Figure 4).

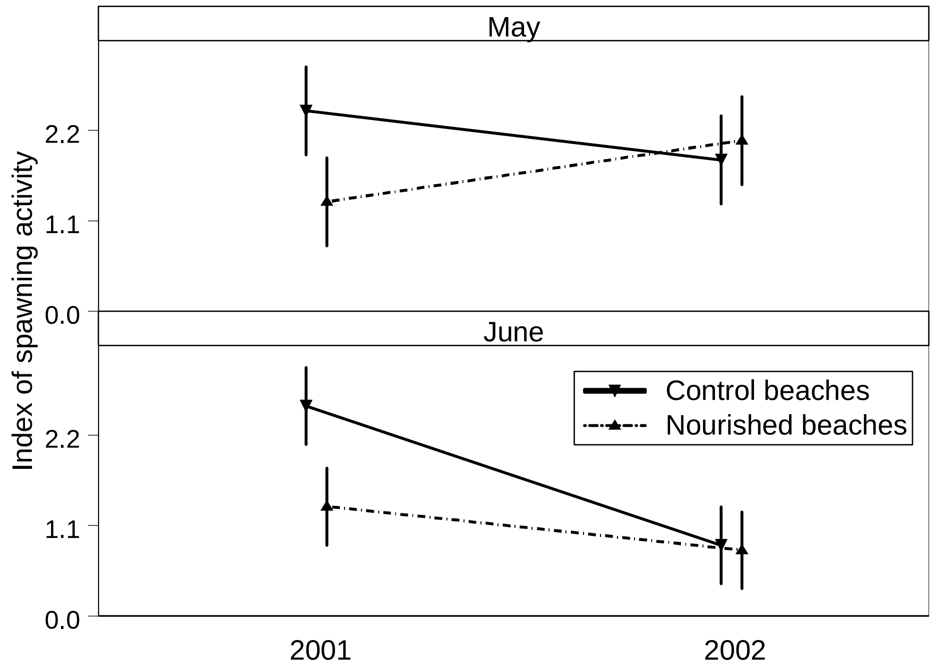

Figure 3. Comparison of spawning activity (no. of spawning females per m^2) on recently nourished beaches (North Bowers and Pickering) and control beaches (Ted Harvey and Kitts Hummock) throughout the spawning season (May and June) for two consecutive years. Symbols represent mean values and vertical lines represent 90% confidence intervals based on an ANOVA.

Table 2. Egg density at North Bowers, Ted Harvey, and Pickering for May and June of 2001 and 2002. Percent of eggs in the surface sediments (0 to 5 cm deep) are presented.

Year	Month	Beach	Egg density 0 to 20 cm deep (no. per m^2)	SE	% eggs in surface sediment (0 to 5 cm)
2001	May	North Bowers	83638.13	16180.29	1.97
		Ted Harvey	351315.72	87910.79	6.63
		Pickering	81257.87	32075.92	2.61
	June	North Bowers	575206.13		10.98
		Ted Harvey	473082.20	37670.72	10.53
		Pickering	715794.42		11.29
2002	May	North Bowers	255267.68	42951.78	1.72
		Ted Harvey	426931.15	33924.50	12.60
		Pickering	393841.16	35709.19	6.88
	June	North Bowers	48803.91	9198.52	4.60
		Ted Harvey	115513.45	27659.20	4.38
		Pickering	66880.35	13759.74	4.95

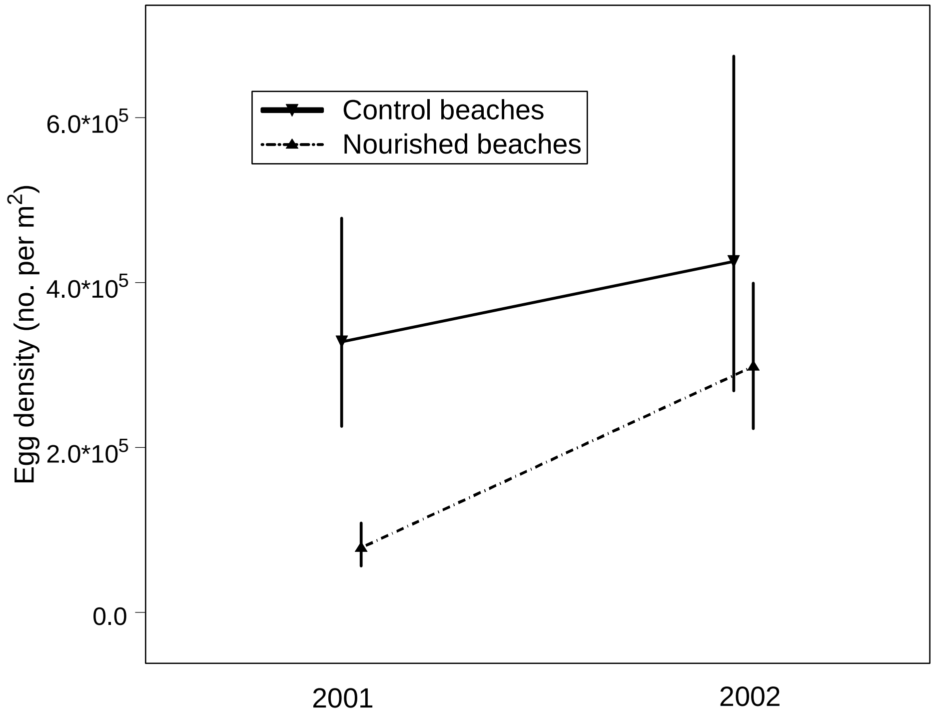

Figure 4. Comparison of egg density on a control beach (Ted Harvey) and nourished beaches (North Bowers and Pickering) at the end of May for two consecutive years. Symbols represent mean values and vertical lines represent 90% confidence intervals based on an ANOVA.

Beach and sediment characteristics at North Bowers

Profile changes – Pre- and post nourishment profiles reveal a 0.20 m increase in elevation on the profile where maximum spawning would occur during spring tides (Figure 5 and 6). Foreshore slope, prior to the nourishment was 4 deg at the North Segment and slightly steeper at the Middle and South Segment (5 deg). After the nourishment, there was an increase in the foreshore slope at the North Segment (5 deg) while the Middle and South Segments remained unchanged (Figures 7 and 8). The steeper slope in the North Segment probably resulted from placement of more fill materials high on the active foreshore rather than from a wave-induced profile adjustment, because there was insufficient time for waves to rework the profile into an equilibrium form.

Data from depth of disturbance rods indicate that the greatest net surface change on the Middle Segment on 15 May, after one tidal cycle, was 10 mm of accretion that occurred near the upper limit of swash. The activation depth was 9 mm. Net surface change on the South Segment on 16 May, after one tidal cycle, was only a few mm; activation depth was <8 mm.

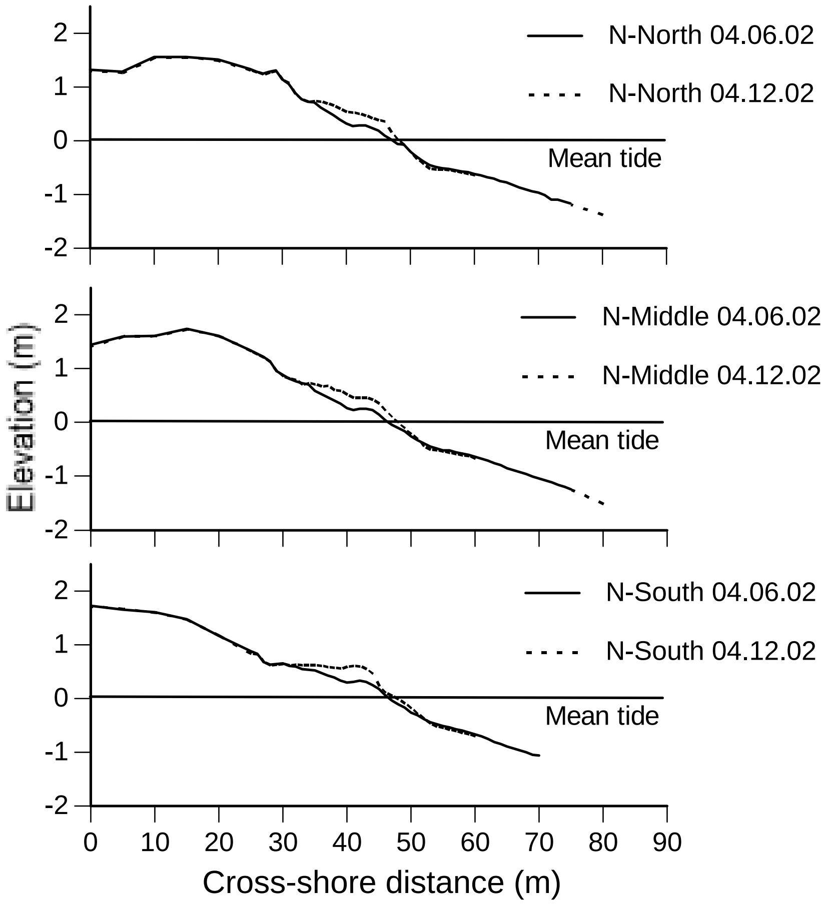

Figure 5. Profiles of the North Segment before (06 April 02) and after (12 April 02) the beach nourishment operation at North Bowers Beach.

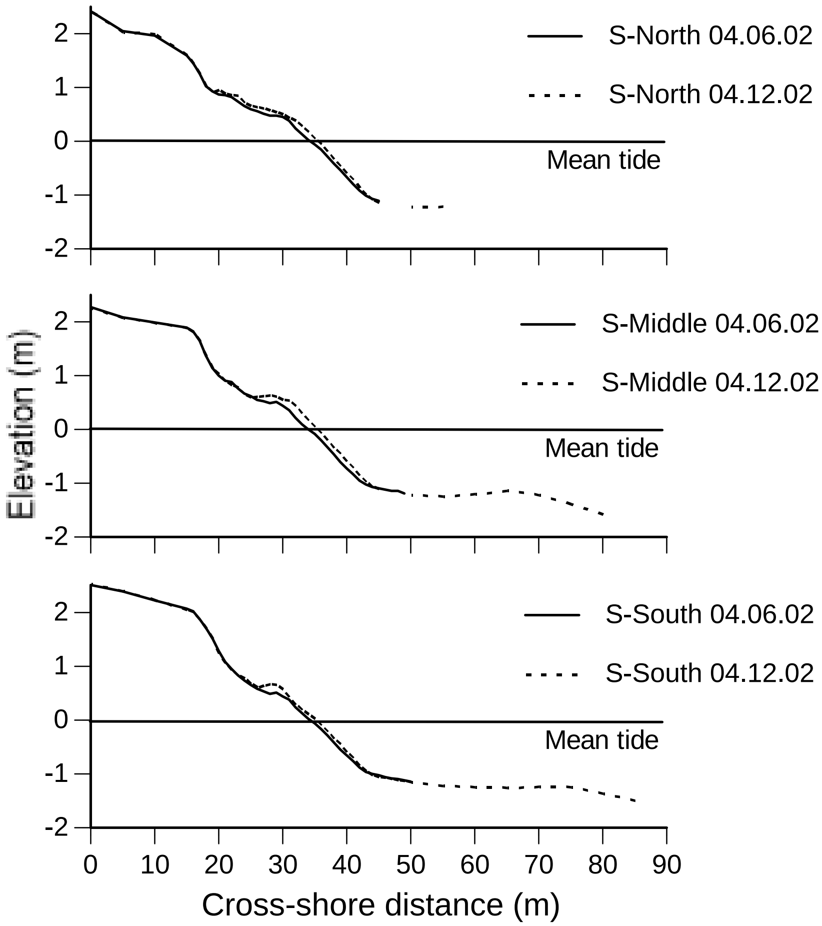

Figure 6. Profiles of the South Segment before (06 April 02) and after (12 April 02) the beach nourishment operation at North Bowers Beach.

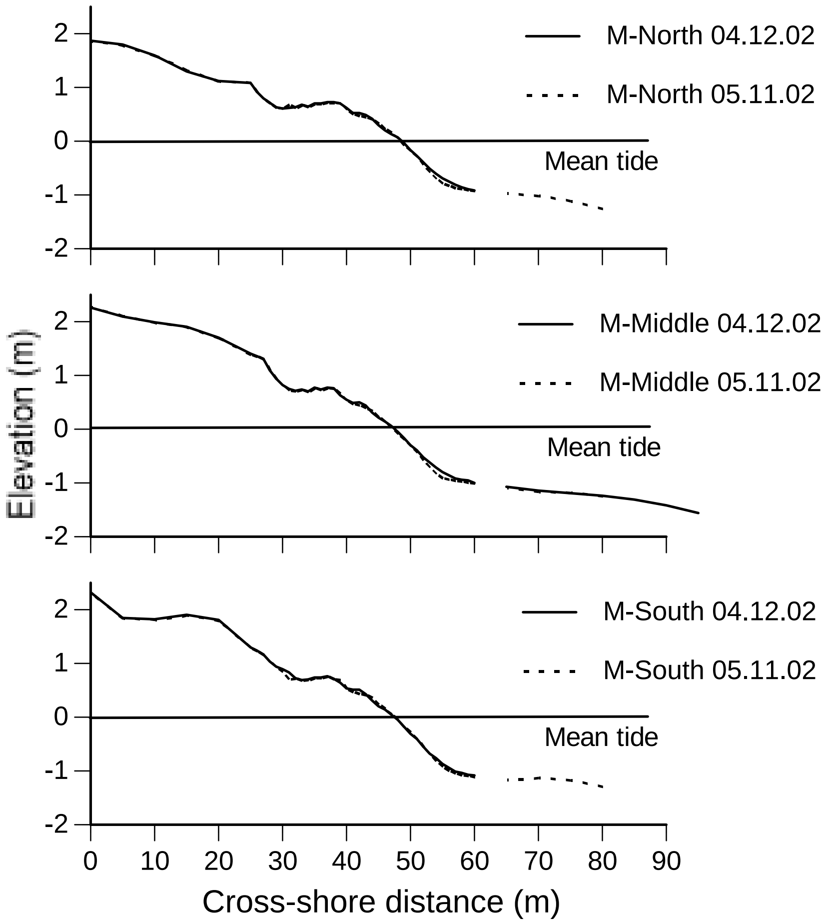

Figure 7. Profiles of the Middle line in the South Segment at North Bowers Beach after the beach nourishment operation (12 April 02) and just prior to the field investigation (11 May 02).

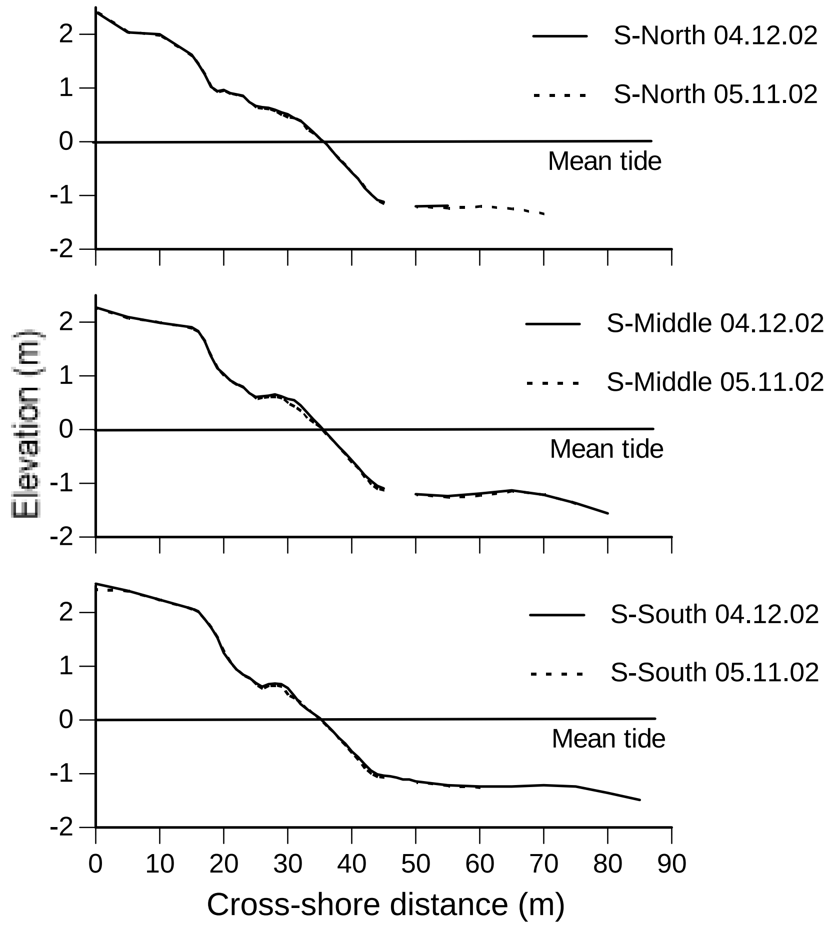

Figure 8. Profiles of the Middle line in the South Segment at North Bowers Beach after the beach nourishment operation (12 April 02) and just prior to the field investigation (11 May 02).

Sediment characteristics **-** Visual observation of the sediment characteristics in the shallow pits dug on 06 April revealed a depth of recent active sediment reworking of 0.10 to 0.16 m below the surface, representing the effect of a previous storm. Pits dug on 12 April, two days after the nourishment operation, revealed a reworked layer of 0.04 m at both the North and South Segments, underlain by the nourished gravel layer 0.05 –0.07 m thick. The limited depth of reworking is expected on an estuarine beach after only two days of low energy waves. Visual observations of the surface gravel on 12 April and 11

May indicate that a significant portion of the gravel was transported into the Middle Segment during this interval, but net change in the elevation of the profiles at all three segments was not significant (Figure 7 and 8). Pits dug in the beach on 15 and 16 May (described below) reveal that the fill sediment had been worked into the beach matrix by wave action.

Sediment samples taken at 0.15 m increments in both the Middle and South Segments (Table 3) reveal that sand is the dominant subfraction and that the percentage of gravel increases with depth and with a lower position on the foreshore. The amounts of gravel are too small to result in much increase in mean grain size and sorting or to affect the cross-shore variability in mean grain size (Table 3), and they would be too small to affect hydraulic conductivity or the shape of the beach profile according to Mason and Coates (2001). The small percentage of gravel near the base of the pit high on the foreshore of the Middle Segment is somewhat anomalous. The gravel at 0.15 m depth, high on the foreshore of South Segment is believed to be attributed to preferential delivery of pebbles to the upper-most portion of the active beach, where they are stranded until high swash energies remobilize that portion of the beach (Nordstrom and Jackson 1993).

Thin, discontinuous clay layers are present on both segments, beginning 0.50 m below the beach surface. These deposits represent the accumulation of fine-grained materials deposited in the earlier fill.

Sediments taken from the scarp on the backbeach are representative of sediments in the previous large-scale nourishment project that have not been reworked by wave action. The mean grain size of the sand fraction is 0.37 mm and the standard deviation is

0.91ϕ. The total sample is 8.1% gravel, giving it a mean grain size of 0.48 mm and a standard deviation of 1.54ϕ. The percentage of gravel in the scarp is greater than occurs at a depth of ≤0.60 m in the High and Middle elevations of the profile in both the Middle and South Segments, implying that the previous fill has been reworked to this depth. The implication is that the absence of gravel in the beach matrix prior to the April 2002 fill was more a function of long-term wave reworking of the previous fill than a lack of gravel in the initial fill sediment. The rapid reworking of the upper 0.10 to 0.20 m of beach between 12 April and 15-16 May 2002, and the resulting elimination of pebbles from most of the higher portions of the foreshore, imply that adding gravel may result in only a temporary change in subsurface characteristics. However, visual observations indicate that there were much larger quantities of gravel on the surface of the beach in May than prior to the April, 2002 fill, so the gravel may still have an effect on site selection by crabs.

Gravimetric sediment moisture values taken at 0.17 m depth at the three locations on the Middle and South Segments on 15 and 16 May are presented in Table 4. The missing data points are during sampling periods at high levels of the tide, when the wells at the lowest elevation were inundated. The moisture content of the sediments at these two low elevations remained high both during the rise and fall of the tide. High tide was at 12:30 on 15 May and 13:00 on 16 May. The sediment moisture values at the upper two elevations on the Middle Segment on 15 May were lower than the moisture values at similar elevations on the South Segment on 16 May.

Table 3. Sediment characteristics from pits dug adjacent to wells on Middle Segment and South Segment on North Bowers.

Middle Segment	High					Middle				Low
Depth below sand surface (m)	0.15	0.30	0.45	0.60	0.75	0.15	0.30	0.45	0.60	0.15
Sand fraction										
Mean (mm)	0.33	0.38	0.48	0.50	0.38	0.41	0.71	0.52	0.49	0.35
Std.dev. (ϕ)	0.56	0.70	0.73	0.93	0.71	0.59	0.90	0.86	0.83	0.74
Total sample										
Mean (mm)	0.33	0.38	0.48	0.61	0.38	0.41	0.77	0.54	0.50	0.37
Std.dev. (ϕ)	0.61	0.75	0.76	1.34	0.71	0.59	1.06	0.92	0.90	0.92
% gravel	0.50	0.50	0.70	7.60	0.00	0.00	4.30	1.30	1.00	2.00
% clay	0.00	0.00	0.00	3.00	1.00	0.00	0.00	0.00	1.00	0.00

South Segment	High						Middle				Low	
Depth below sand surface (m)	0.15	0.30	0.45	0.60	0.75	0.90	0.15	0.30	0.45	0.60	0.15	0.30
Sand fraction												
Mean (mm)	0.40	0.45	0.40	0.33	0.48	0.39	0.42	0.38	0.43	0.43	0.44	0.69
Std.dev. (ϕ)	0.91	0.53	0.72	1.03	0.91	0.85	0.94	0.70	0.82	0.93	1.04	1.21
Total sample												
Mean (mm)	0.43	0.45	0.40	0.36	0.50	0.42	0.43	0.39	0.44	0.49	0.47	0.97
Std.dev. (ϕ)	1.10	0.53	0.72	1.26	1.02	1.03	1.00	0.73	0.89	1.29	1.17	1.67
% gravel	2.50	0.00	0.00	3.60	2.20	2.50	0.90	0.40	1.20	4.40	2.50	15.0
% clay	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	1.00	0.0	1.00

Tide and Water Table Characteristics -- Mean tide range near the study site is 1.6 m, spring range is 1.8 m and mean tide is 0.82 m (NOAA, 2002a). The predicted high tide for 15 and 16 May was 1.2 m (relative to MLLW) (NOAA, 2002a). Water level data (relative to mean tide) gathered from the Middle Segment (15 May) and the South Segment (16 May) are presented in Figure 9. The measured height of the tide was lower than predicted on both days. The measured height of the tide on 15 May was lower than on 16 May. Winds on 15 and 16 May were offshore during the monitoring period. Resultant winds speeds, recorded at Wilmington, DE, were 2.7 m s^{-1} for both days (NOAA, 2002b). Wave heights during both monitoring periods were less than 0.02 m. The 10-min averages of water level during both monitoring periods reveal several characteristics of beach water tables (Neilson 1990). First, the minimum level of the water table at the lower elevation wells at the Middle and South Segment (Figure 10) is higher than the low tide level for the two monitoring periods (Figure 9). Second, the rate of rise of the beach water table in the lower elevation wells is steeper than the rate of fall. Third, there is a time lag of the arrival of the water table wave between the lower and middle elevation wells.

Table 4. Sediment moisture values, 0.17 m below the sand surface, in percent for each monitoring period at Bowers Beach.

Segment/Date/Time	Moisture Content (%)		
Middle Segment	High	Middle	Low
15 May 02			
07:45	2.6	3.6	19.6
09:15	2.5	3.2	18.9
10:45	2.7	5.0	19.5
12:15	3.6	3.5	-
13:45	3.5	3.7	18.8
15:15	2.9	3.1	17.6
16:45	3.2	3.1	19.9
18:15	2.8	2.8	19.7
South Segment	High	Middle	Low
16 May 02			
08:30	5.1	6.2	17.4
10:00	5.9	7.4	18.2
11:30	7.4	5.5	-
13:00	4.7	5.6	-
14:30	5.0	6.4	-
16:00	5.2	6.0	15.8
17:30	5.5	6.8	17.2
19:00	5.2	4.8	18.6

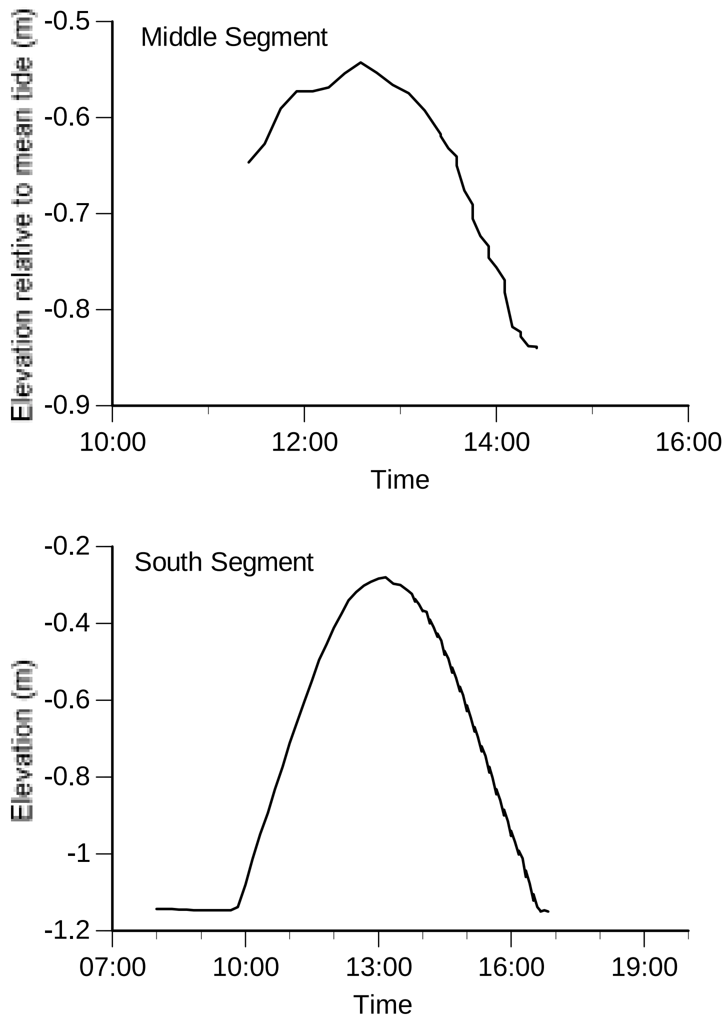

Figure 9. Tidal elevation changes on the Middle Segment (15 May 02) and the South Segment (16 May 02) of North Bowers Beach.

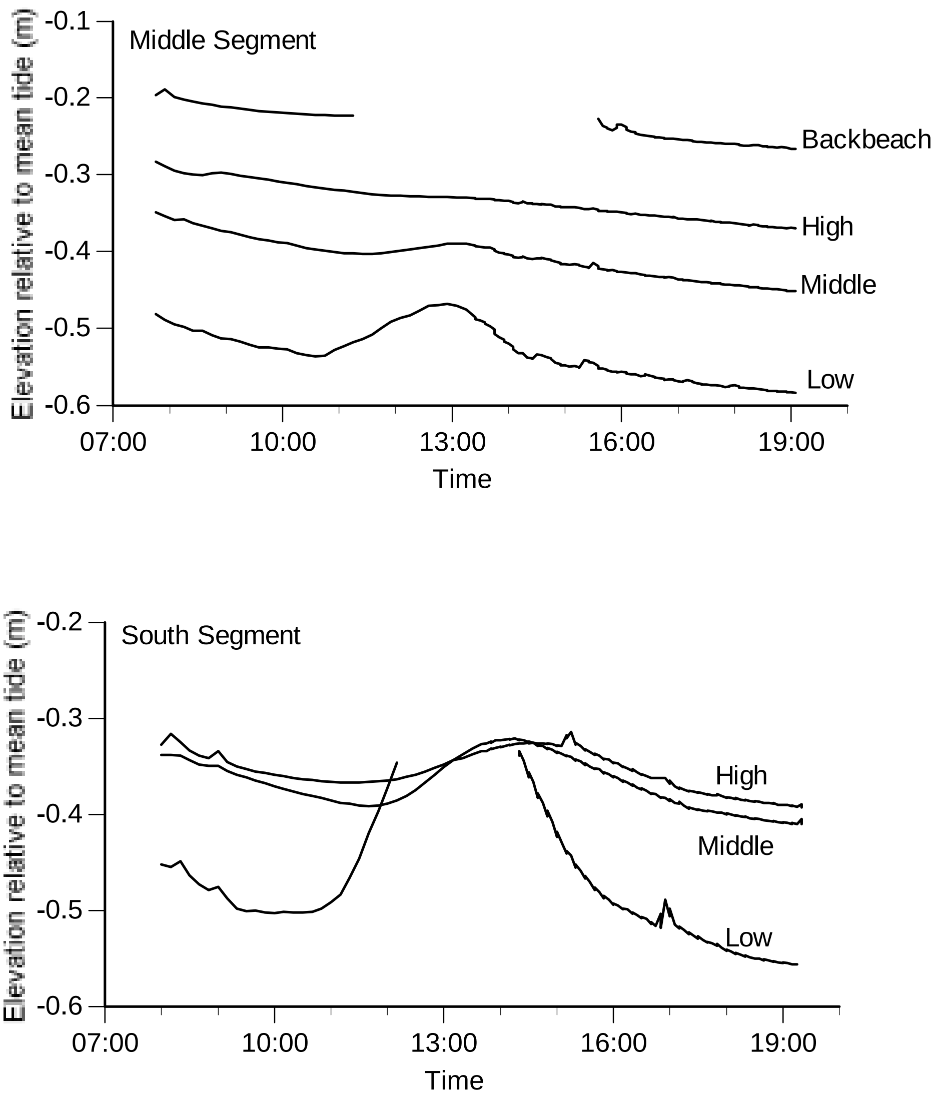

Figure 10. Water table elevation changes on the Middle Segment (15 May 02) and the South Segment (16 May 02) of North Bowers Beach.

Figure 11 reveals the elevation of the water table relative to the sand surface (0 m) and the location of the buried egg pouches (-0.17 m). The egg pouch buried low on the foreshore was in sediments that were saturated during 50 minutes of the tidal cycle on the Middle segment and for most of the tidal cycle on the South Segment (Figure 11). The saturated moisture content for sand is approximately 25%, assuming a porosity of 0.40 (Sherman 1990). During the falling tide on the Middle Segment, the water table elevation reached a maximum of 0.10 m below the elevation of the egg pouch on the lower foreshore, but this difference did not result in a reduction in the moisture content of the sediments (Table 4). At the high and middle elevations on both the Middle and South Segments, the water table elevation was well below the elevation of the egg pouches. The moisture content of the sediments at the high and middle elevations was lower on the Middle Segment compared to the South Segment.

The capillary fringe can be important to egg viability because the zone can provide a layer of moist sediments above the zone of saturation for successful egg development. For the range of grain diameters found at the middle elevation on the Middle and South Segment, the thickness of the capillary fringe would be approximately 0.23 m above the water table.

Figure 12 presents data for the water table profile, during the falling tide, for selected time periods during the time series depicted in Figure 9. The profile from the Middle Segment reveals a water table that is sloped in the seaward direction. Calculation of the hydraulic gradient from the piezometers installed on the Middle Segment reveal that the water table flow was directed seaward for most of the tidal cycle. The direction of flow was landward during the high tide monitoring period between the middle and low elevation wells. The slower rate of drainage of the water table relative to the fall of the tide is evident in both profiles. The ability for the beach to drain is a function of the permeability of the sediments.

Hydraulic conductivity is a measure of the permeability of the porous medium (Todd 1980). Estimates of hydraulic conductivity (K) were obtained from the empirical formulation of Bear (1972):

$$K = \left(\frac{\rho g}{\mu}\right)\frac{n^3}{(n-1)^2}\left(\frac{d^2}{180}\right)$$

where ρ is the density of the fluid (1009 kg/m^3), μ is the dynamic viscosity (10^{-3} N s m^{-2}), *n* is the porosity (0.40), and *d* is the median sediment diameter. The hydraulic conductivity for the saturated zone ranged from 0.001 to 0.002 m s^{-1} in on both segments. These values are similar to those found for other foreshore environments. Differences in hydraulic conductivity were found 0.30 – 0.45 m below the sand surface at the middle elevations of the two segments. These regions were unsaturated during the two monitoring periods, but would be within the saturated zone during the higher spring tide conditions predicted for late May (NOAA 2002a). The hydraulic conductivity of the sand fraction in the Middle Segment was higher (0.003 – 0.005 m s^{-1}) compared to the South Segment (0.001 – 0.002 m s^{-1}).

Egg viability and development

More pouches were lost on North Bowers than on Ted Harvey due to tearing or failing to relocate (Table 5). Most of the losses occurred in the middle elevation where high levels of spawning would be expected to disturb the pouches and would explain the losses. However, Ted Harvey received at least as much spawning as North Bowers, probably more, and because Ted Harvey is steeper and narrower the spawning is likely to be more concentrated in the middle elevation on Ted Harvey than on North Bowers. Perhaps coarser sediment on Ted Harvey, which armors the beach somewhat, protected the pouches from disturbance and dislocation.

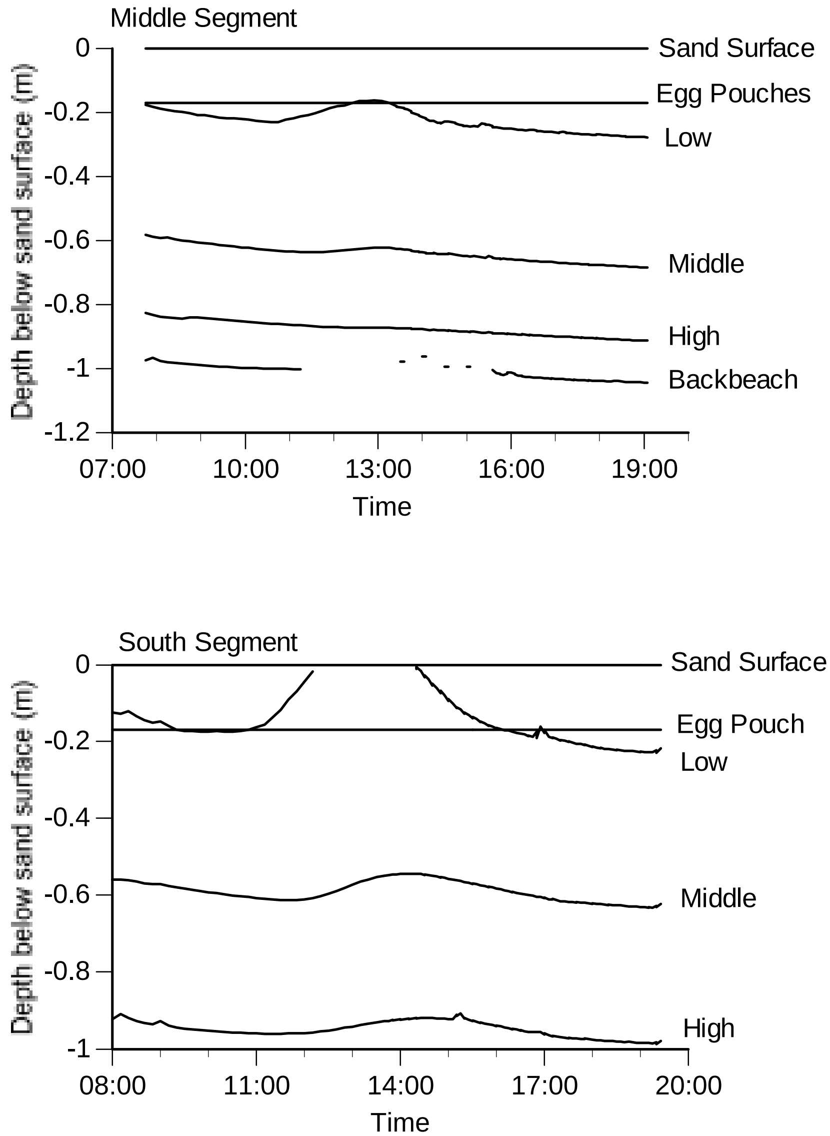

Figure 11. Depth of the water table and egg pouches below the sand surface measured onthe Middle Segment (15 May 02) and South Segment (16 May 02) on North Bowers.

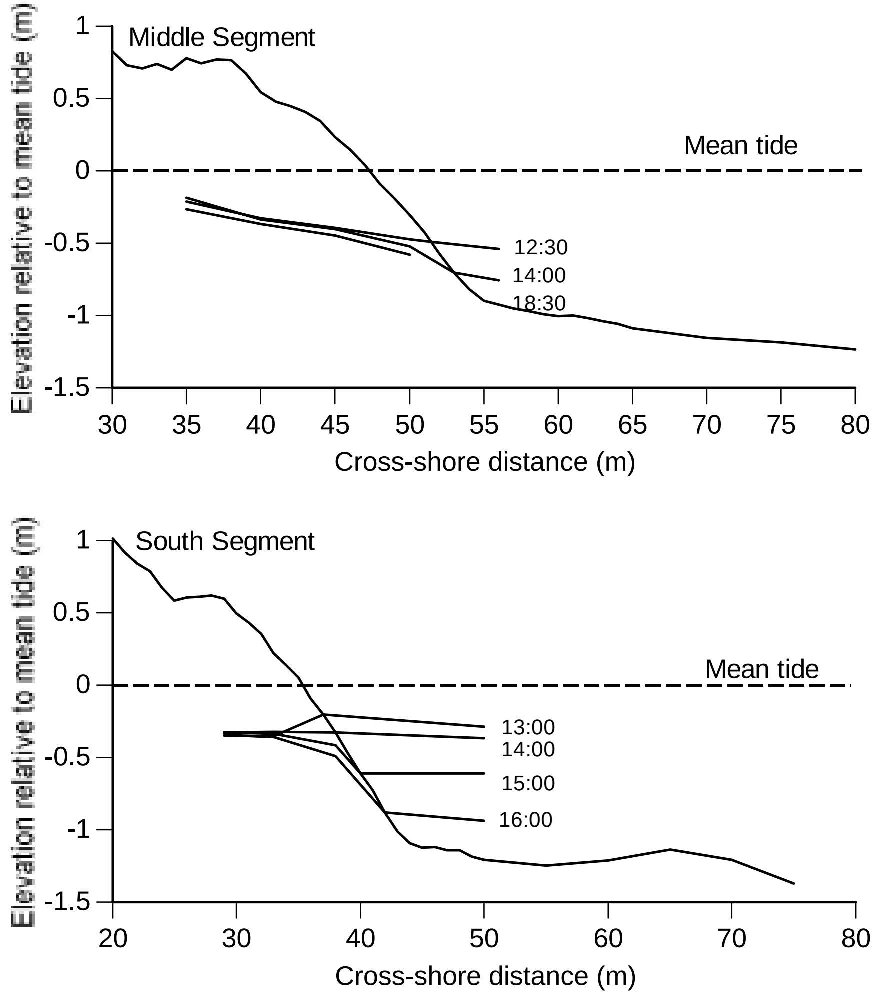

Figure 12. Elevation of the beach water table during the falling tide on the Middle Segment (top) and the South Segment (bottom).

Table 5. Distribution of egg transplant pouches that were torn or missing. In the middle section of North Bowers, one cross-shore transect was not located probably because of incorrect recording of bearings or distances, so the three pouches were not included in this table.

Beach	Section	Elevation	No. torn or missing pouches	No. of pouches available for retrieval
North Bowers	South	Low	1	4
		Middle	2	4
		High	0	4
	Middle	Low	0	3
		Middle	2	3
		High	1	3
	North	Low	0	4
		Middle	0	4
		High	0	4
Ted Harvey	South	Low	0	4
		Middle	0	4
		High	0	4
		Low	1	4
		Middle	0	4
		High	0	4

As expected, egg development was highest in the middle elevation (Table 6, Figure 13A). Eggs in the lower elevation appeared to remain viable, but did not develop to the embryo stage (Table 6, Figure 13B). There was substantial egg death in the high elevation (Table 6, Figure 13C) largely due to desiccation, but macrofauna were present frequently in high elevation pouches, i.e., nematodes, fly larvae, and beetle adults and larvae. It is not clear whether the macrofauna were predators or scavengers.

Table 6. Rates of development to embryo or larval stage, egg viability, and egg mortality as determined by an egg transplant study where eggs were removed from a common source and buried 15 to 20 cm deep at three cross-shore positions at North Bowers and Ted Harvey beaches. The cross-shore positions were defined as proportions of beach width: low position = 0.2*beach width, mid position = 0.5*beach width, and high position = 0.8*beach width.

Beach	Segment	Cross-shore position	Development rate	SE	Egg viability rate	SE	Egg mortality rate	SE
North Bowers	Middle	Low	0.00	0.0017	1.00	0.0015	0.00	0.0000
		Mid	0.45		0.35		0.16	
		High	0.27	0.2626	0.21	0.1903	0.51	0.0731
	North	Low	0.04	0.0281	0.74	0.2138	0.22	0.1880
		Mid	0.36	0.2179	0.20	0.0910	0.44	0.1557
		High	0.18	0.1050	0.30	0.0515	0.50	0.1469
	South	Low	0.00	0.0001	1.00	0.0001	0.00	0.0000
		Mid	0.60		0.40		0.01	
		High	0.00	0.0040	0.40	0.0359	0.59	0.0329
Ted Harvey	North	Low	0.00	0.0001	0.95	0.0445	0.05	0.0444
		Mid	0.21	0.1041	0.64	0.1560	0.14	0.0527
		High	0.01	0.0063	0.09	0.0290	0.90	0.0239
	South	Low	0.00	0.0000	1.00	0.0006	0.00	0.0006
		Mid	0.45	0.1605	0.39	0.1194	0.17	0.0424
		High	0.04	0.0436	0.16	0.0537	0.79	0.0661

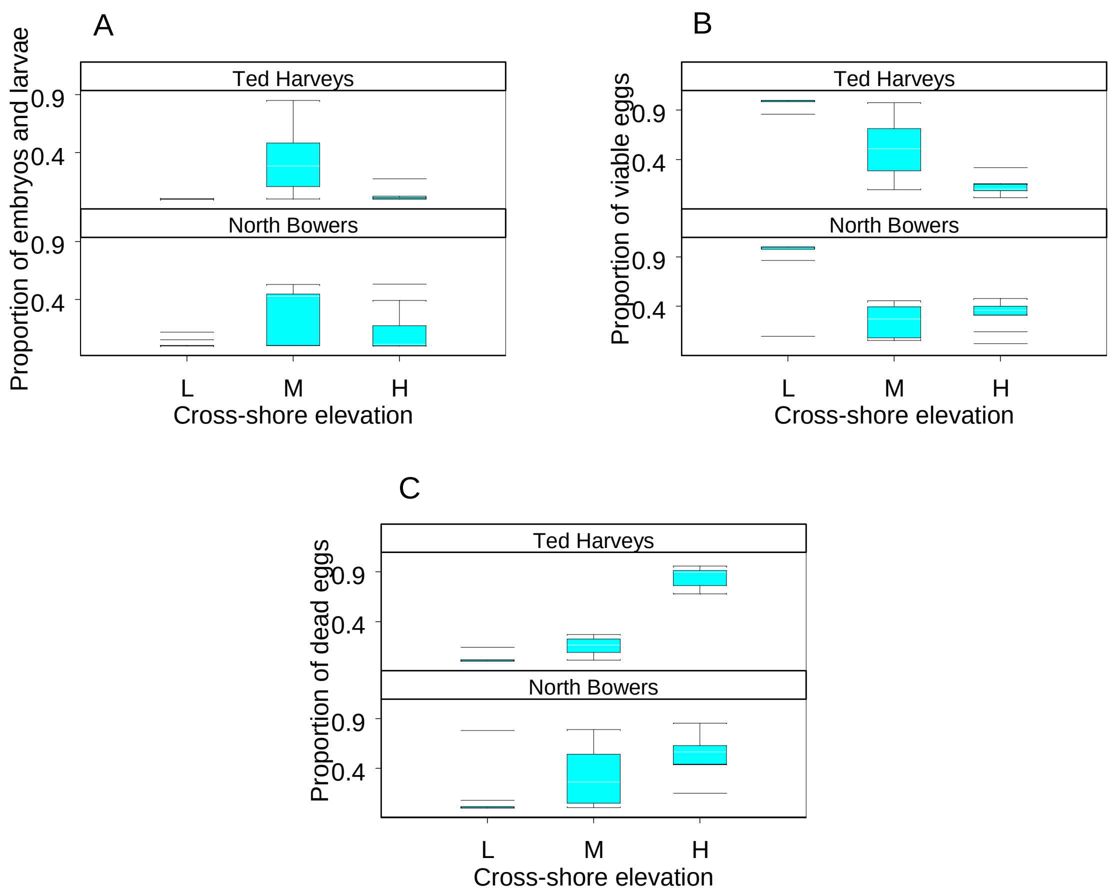

Figure 13. Results from an egg transplant experiment where eggs from a common source beach were transplanted in pouches to two other beaches. Pouches were buried at three positions: 0.2 (L), 0.5 (M), or 0.8 (H) of foreshore width. Box plots show the proportion of eggs that developed to embryos or larvae (A), the proportion of eggs that remained viable (B), and the proportion of eggs that died (C).

Between beach differences seem to be limited to high elevation pouches where there was slightly higher development on North Bowers (Figure 13A) and higher egg death on Ted Harvey (Figure 13C). However, there was some development to trilobite larvae stage on North Bowers, but very little development to larval stage on Ted Harvey (Figure 14).

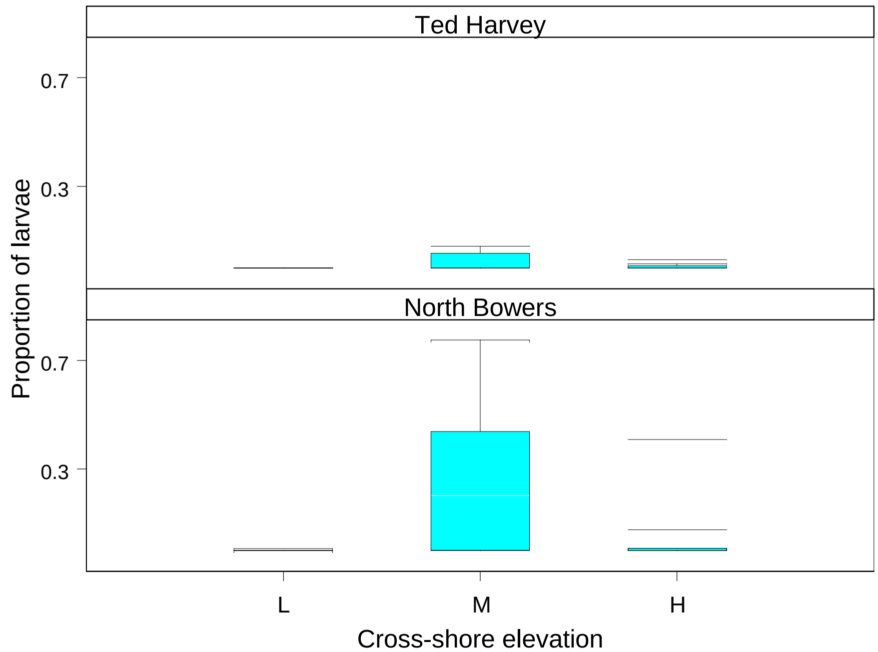

Figure 14. Results from an egg transplant experiment where eggs from a common source beach were transplanted in pouches to two other beaches. Pouches were buried at three positions: 0.2 (L), 0.5 (M), or 0.8 (H) of foreshore width. Box plots show proportion of eggs that developed to larval stage.

The actual number of eggs that remained viable and developed is a function of rates of viability and development and egg abundance across the foreshore. The distribution of eggs across the foreshore varied among the beaches (Figure 15). By integrating the product of egg viability and development rates (shown in Table 6) and egg abundances (shown in Figure 15) we predicted actual egg viability and development at Ted Harvey and North Bowers (Table 7). Although the density of eggs was substantially higher at Ted Harvey than North Bowers (Table 2), the actual egg development was predicted to be higher at North Bowers because eggs developed at a higher rate at North Bowers compared to Ted Harvey.

Table 7. Predicted number of eggs that were deposited and remained buried at least 5 cm deep by end of May that subsequently would (1) remain viable as an egg, embryo, or larvae or (2) develop to embryo or larval stage by mid-June. (Development is a subset of viability.) Egg densities were estimated from beach sampling and rates of viability and development were derived from a transplant experiment where eggs were transplanted from a common source to Ted Harvey and North Bowers beaches.

Beach	Segment	Predicted viability	Predicted development
Ted Harvey	South	732371	329863
	North	751097	173014
North Bowers	South	651709	595095
	Middle	990980	453590
	North	628032	400023

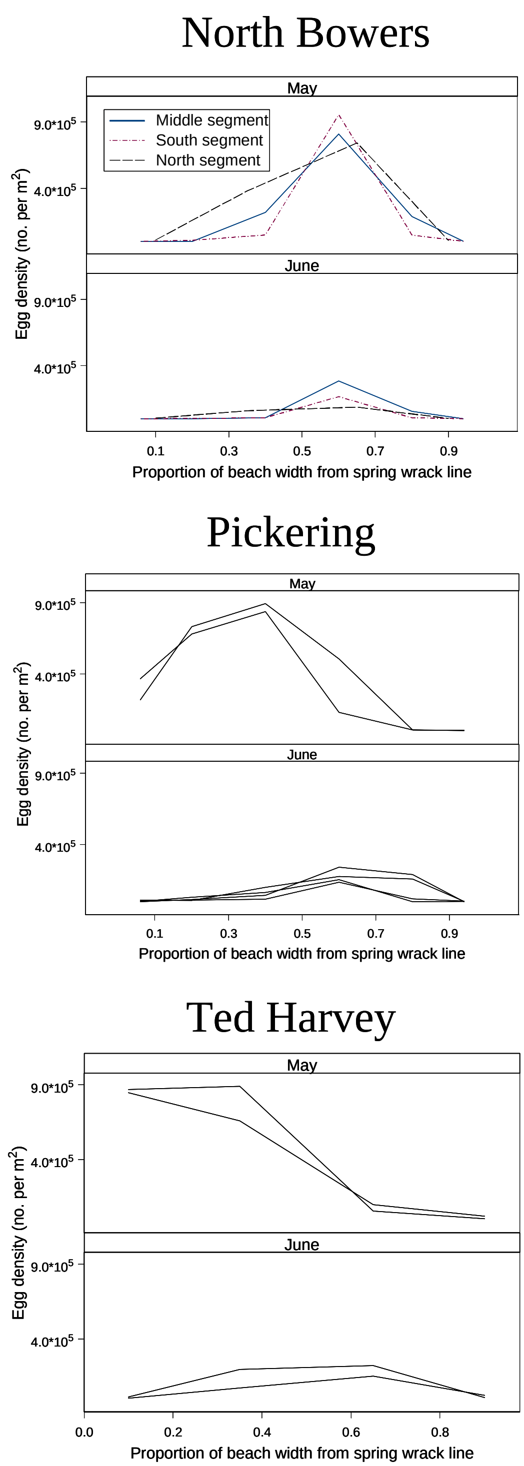

Figure 15. Egg density across the beach foreshore at North Bowers, Pickering and Ted Harvey. Distance across the foreshore is presented as a fraction or proportion of the width in reference to the spring wrack line.

DISCUSSION

Study results showed a stable or increasing amount of spawning activity at beaches that were recently nourished (North Bowers and Pickering) while spawning activity at previously nourished (i.e., control) beaches (Ted Harvey and Kitts Hummock) declined from 2001 to 2002. Results also showed that beach characteristics affect egg development and viability. These results are consistent with the hypotheses that 1) horseshoe crabs can sense and are attracted to recently nourished beaches and 2) egg development and viability are affected by beach-specific moisture characteristics. Horseshoe crabs are thought to be generalists. There would be evolutionary advantages for an estuarine species to be capable of exploiting newly created habitat whether artificially or naturally created. Horseshoe crabs are known to be sensitive to geochemical factors (Botton et al. 1988), which provides a possible mechanism for beach selection. Higher egg development rates at North Bowers seem to indicate that desiccation is the greater threat to egg development and that there might be an advantage to spawning on beaches where the upper foreshore is less prone to drying. It is not clear, however, whether the subtle differences in egg development and viability would accrue sufficient fitness to result in an evolutionary advantage.

Intertidal zones of exposed beaches comprise several regions based on interstitial moisture content of the sediments (McLachlan 1983). On estuarine beaches, the upper elevations of the foreshore (from the upper limit of swash at spring tide to the upper limit of swash at neap tide) are characterized by low moisture conditions. The region is perhaps the most harsh environment for egg viability. The water table monitoring at both the Middle and South Segments occurred during the lower high tide of a spring tidal cycle; although the evening tide was higher (1.65 m). The height of the tide was also lower than predicted, influenced by offshore low speed winds and low wave activity. The upper limit of swash during the monitoring period on the Middle Segment was 0.5 m below the lower sampling point at 52 m from the baseline (0 line on Figure 7). On the South Segment the upper swash limit was just above the lower sampling point or 37 m from the baseline (0 m on Figure 8). The large amount of egg desiccation in the upper elevations would be influenced by the lack of moisture in the upper centimeters of the beach matrix.

The lower foreshore, near the break in slope that separates the foreshore from the low tide terrace, is a region of high saturation. The water table elevations recorded in the lowest elevation wells at high tide on both Segments were near or exceeded the sand surface elevation. The moisture content of the sediments remained high, but not saturated during the remainder of the tidal cycle. The water table outcrop (location on the lower portion of the foreshore where the water table exits the beach matrix) was just bayward of the two wells. Eggs in these two locations remained viable but did not develop.

The mid-foreshore region is an area where the greatest egg development occurred at North Bowers, and development was slightly higher in the South Segment. The measured water table elevation did not vary significantly at the middle elevations in the two Segments but there was slightly greater moisture content of the sediments at the depth that the egg pouches were buried in the South Segment.

Differences in weather patterns, particularly wind, present a confounding factor in the between year differences in spawning activity. Wave-generating onshore winds during May 2001 seemed to deter spawning more on North Bowers and Pickering, which are subject to higher wave energy than Ted Harvey and Kitts Hummock (D. R. Smith, unpublished data). So the 2001 spawning pattern was depressed in May, except for Ted Harvey and Kitts Hummock, followed by higher and more uniform spawning in June. In 2002, wind seemed to be less of a factor with >0.33 m waves on only one of the 12 survey nights. So it is not surprising that spawning was higher during 2002 than 2001 as evidenced by egg densities. However, appearance that overall spawning activity decreased at Ted Harvey and Kitts Hummock, but not at North Bowers and Pickering indicates that some redistribution had occurred. Whether the redistribution was in response to nourishment is not firmly established, but the greater amounts of gravel on the surface of the beach, which is a diagnostic of low energy conditions, could have drawn crabs to North Bowers in 2002.

On North Bowers, rate of egg development to larvae was greater and egg desiccation was less than on Ted Harvey. Because Ted Harvey with a coarse sediment distribution was well drained and had a low water table, egg desiccation in the high elevation zone was substantial. The high elevation zone on North Bowers seemed to retain moisture and prevent some egg desiccation. Temperature differences are a possible explanation for the higher rate of egg development to larvae stage in the middle elevation of North Bowers. Temperatures could have been more stable on North Bowers because of increased moisture.

Sediment cores (0.20 m long) taken in 2001 at mid-foreshore at Ted Harvey reveal that the sediments are coarser and more poorly sorted compared to the sediments in the Middle Segment of North Bowers. The coarser, more poorly sorted sediments at

Ted Harvey will result in lower porosity and higher hydraulic conductivity and a better drained beach. The width of the capillary fringe will be lower because of the coarser grain sizes thus reducing the moisture potential of the beach matrix.

This project represents the first study of the effects of nourishment on horseshoe crab spawning that included temporal and spatial controls. The results, although consistent with the hypothesis that horseshoe crabs respond favorably to a recently nourished beach, did not lead to detailed guidelines for beach restoration for horseshoe crab spawning habitat due to the limit in the number of factors that could be manipulated at one time in field studies and the challenge of controlling for potentially confounding factors, such as weather. Our conclusions, which are mostly qualitative in nature, should be subject to testing through continued study and monitoring. In particular, monitoring of horseshoe crab spawning activity should continue at North Bowers, Pickering, Kitts Hummock, and Ted Harvey to observe the temporal spawning patterns in relation to beach nourishment. And additional experimental nourishments should be undertaken to further identify and quantify the factors that affect whether nourishment will enhance or degrade a beach as horseshoe crab spawning habitat.

CONCLUSIONS

1. Small volumes of nourished sediment do not cause sufficient change in beach slope to alter suitability for spawning.
2. The effect of adding small amounts of gravel is temporary. The gravel is quickly incorporated into the wave-reworked sand on the upper beach, but it results in a

conspicuous change in the amounts of gravel and the appearance of the surface and at a depth on the lower foreshore. This gravel may affect site selection.

3. Grain size may affect egg development through its impact on egg development especially in the upper, dryer foreshore. Finer sizes may be more important for egg viability because of moisture retention.
4. The source of sediment for nourishment should be chosen to reflect a coarse estuarine beach. The nourished sediment should have a gravel subfraction and have a mean sediment size of 0.35 to 0.50 mm in the sand fraction.
5. Beach nourishment can have a positive effect on site selection and egg viability, but more research is required to assess optimum size of fill materials and timing of the operations.

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