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Mapping Migratory Wading Bird Feeding Habitats using Satellite Imagery and Field Data, Eighty-Mile Beach, Western Australia

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ABSTRACT

WADE, S. and HICKEY, R., 2008. Mapping migratory wading bird feeding habitats using satellite imagery and field data, Eighty-Mile Beach, Western Australia. *Journal of Coastal Research,* 24(3), 759–770. West Palm Beach (Florida), ISSN 0749-0208.

Eighty-Mile Beach is one of the 10 most populous sites for migratory birds in the Asian–Australasian Flyway. The birds come to Eighty-Mile Beach's tidal mudflats to feed on benthic organisms during their nonbreeding period prior to embarking on a 10,000–15,000-km migration to their breeding grounds in the Arctic. To better understand migratory birds' preferences for areas on the beach, satellite imagery was used to predict grain size and benthic invertebrate distributions. These data were statistically compared with data collected in the field to determine the accuracy of the predictions. Relationships were apparent between compared data, especially in respect to the actual benthic invertebrate distribution. Finally, feeding areas for different bird species were mapped according to where their favored foods would be found. Knowing where the birds should be feeding will help prioritize research and conservation efforts on Eighty-Mile Beach.

ADDITIONAL INDEX WORDS: *Landsat, remote sensing, mudflats, tidal, GIS.*

INTRODUCTION

The health of coastal wetland environments has become a global concern in recent years. Wetlands protect shorelines from wave action, lessen the impact of floods, and provide habitat for numerous plant and animal species (MOORES, 1999). Tidal mudflats located in these wetlands are also key to the survival of many species of migratory shorebirds. The mudflats provide the much needed benthic food supply that the birds fly thousands of kilometers to consume (BARTER, 2002). A specific area of concern in recent years is the Asia–Australasian flyway (RAMSAR, 2004). This flyway covers more than 20 countries, extending from the northern areas of Siberia to the southern areas of Australia and New Zealand. Scientists have estimated that this flyway supports more than 5 million migratory shorebirds (BARTER, 2002).

One of the top 10 most populous stopovers for migratory shorebirds in the Asian–Australasian Flyway is Eighty-Mile Beach, Western Australia (AUSTRALIAN DEPARTMENT OF ENVIRONMENT AND HERITAGE, 1998). Eighty-Mile Beach is a primary nonbreeding area for shorebirds that supports approximately 500,000 birds during each season and has received considerable attention since being listed by RAMSAR (2004) as a wetland of international importance in 1990 (AUSTRALIAN DEPARTMENT OF ENVIRONMENT AND HERITAGE, 2001). With the growing tourist industry, frequent use of the beaches in the area, and the possibility of an increased agriculture industry behind Eighty-Mile Beach, identifying management issues (prior to degradation) for the mudflats is vital to the survival of these shorebirds.

Migratory birds are known to frequent Eighty-Mile Beach because of the abundance of benthic organisms, their primary food source (PEARSON, HICKEY, and HONKOOP, 2005). Benthic organisms are the worms, bivalves, crustaceans, and various other macroinvertebrates that live in the tidal mudflats. If the benthic organism distribution can be identified and mapped, then prioritizing the management of such a large area for migratory birds can be addressed. Recently, field studies in Australia's Eighty-Mile Beach and Roebuck Bay have been conducted to address benthic and bird distributions (HICKEY, 2002; HONKOOP *et al.,* 2006).

PROJECT OBJECTIVES

Managing areas that encompass two continents and various island nations to preserve migratory shorebirds is a daunting task. The vast and remote area of Eighty-Mile Beach generates numerous conservation and logistical complications. Thus, the primary objective of this study was to test the hypothesis that satellite imagery could be useful in mapping the intertidal zone when combined with limited field data.

In particular, statistical testing was used to quantify the

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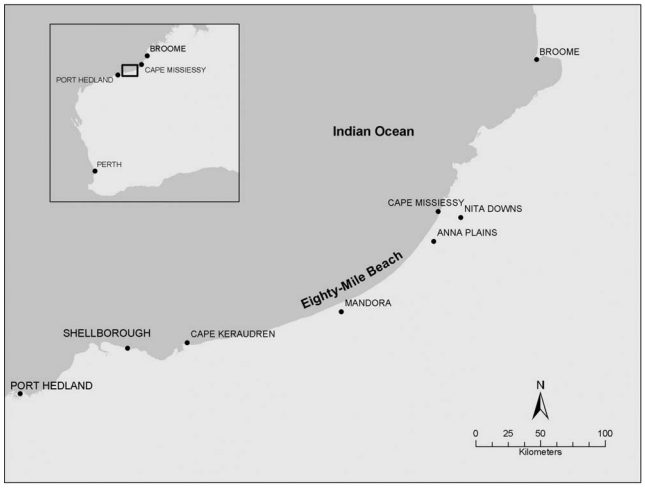


Figure 1. Location of Eighty-Mile Beach within Western Australia.

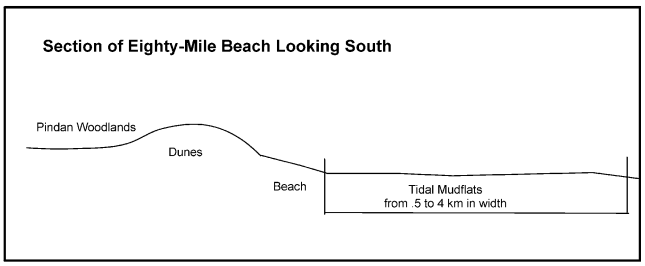


Figure 2. Cross section schematic of Eighty-Mile Beach illustrating the relationships between the pindan woodlands, dunes, sandy beach, and variable-width mudflats.

relationships between the satellite imagery and field data consisting of sediment size and benthic invertebrate distributions. It is important to note that the areas sampled on Eighty-Mile Beach comprised less than half of the length of the beach (75 of 230 km), and only a small fraction of that 75 km was actually sampled.

Should relationships exist between the imagery and field data, migratory bird feeding zones could then be mapped for the entire length and width of Eighty-Mile Beach—providing an invaluable tool for targeting either research or management. It should be emphasized that the focus of this paper is the application of remote sensing to mudflat mapping and evaluation.

SITE DESCRIPTION AND ENVIRONMENTAL BACKGROUND

Eighty-Mile Beach is located in the northwest of Western Australia (Figure 1). It is 220 km long, and located 130 km east northeast of Port Hedland and 142 km south southwest of Broome.

The Eighty-Mile Beach region is characterized by extensive tidal flats with low sand dunes. The plains behind the coastal dunes are dominated by natural grasslands (now strongly influenced by the introduced buffel grass) that are used for some of the most productive cattle ranching in the region (Pepping, 1999) and are also of importance to a few species of migratory shorebird such as little curlew, *Numenius minutes,* and oriental pratincole, *Glareola maldivorum* (Sitters *et al.,* 2004). The grasslands merge to Pindan woodlands; the combined grasslands and Pindan woodlands form a narrow but fertile strip separating Eighty-Mile Beach from the Great Sandy Desert. Located midway along the beach is a small mangrove community.

Eighty-Mile Beach can be considered a reflective beach (Honkoop *et al.,* 2006; McLachlan, 1990). The sediments are primarily shell fragments (carbonate) with only traces of fine sand (Pearson, Hickey, and Honkoop, 2005). The tides are large and semidiurnal, with a daily vertical range of approximately 6 m. Spring tides of 8 to 10 m can leave 0.5 to 4 km of mudflat exposed at low tide (Figure 2) (Western Australian Department of Planning and Infrastructure, 2004). The extensive mudflats provide an ideal habitat for benthic invertebrates and, therefore, are one of the most important wetlands for migratory shorebirds in northwestern Australia.

The climate at Eighty-Mile Beach is semiarid monsoonal. The mean annual rainfall is less than 400 mm, predominantly falling between November and June. The monthly maximum temperatures range between 28.2°C in July and 36.1°C in December. The minimum range is between 11.7°C in July and 25.5°C in January (Australian Bureau of Meteorology, 2000).

Cyclones are frequent in the area and bring heavy rainfall and strong winds. Cyclonic disturbances in the Eighty-Mile Beach area normally occur from December through April (Pepping, 1999). These intertidal systems have developed a capacity to withstand cyclonic events even though the impact of cyclone activity can be considerable (Pearson, Hickey, and Honkoop, 2005). In addition to the physical changes of the beach, the benthic invertebrates living in the top few centimeters (which the birds feed on) of the mudflats may be greatly depleted in the short term while the deeper living fauna remain undisturbed (Jennings, Kaiser, and Reynolds, 2001). Cyclones can also have an effect on the mudflat composition; banks of mud will build up on the mudflats in periods of relatively calm wind and wave conditions, and then erode away in more intense weather. These actions can significantly change benthic distributions (Pearson, Hickey, and Honkoop, 2005).

Benthic Organisms

The word "benthos" is a term for organisms that are attached to or resting on bottom sediments (Fairbridge, 1966). Three modes of life exist among benthic communities: organisms that attach to firm substrates, organisms that are free moving along the seafloor (*epifauna*), and organisms that burrow within the sediments (*infauna*).

The distribution of benthic fauna in the intertidal sediments is not as well known as that of vegetation (Eisma, 1998). Birds depend on benthic organisms for survival, so un-

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derstanding their distribution on the mudflats should help determine what makes certain areas on the mudflats more preferable to specific species. SANDERS (1958, 1960) was one of the first to recognize that there was a relationship between benthic group distribution and sediment grain sizes, particularly with deposit feeders. Other studies have determined that individual species numbers and diversity vary with sediment conditions in various coastal habitats (DALE, 1992; HOBERG, 1986; MCLACHLAN, 1996; SNELGROVE and BUTMAN, 1994; WOODIN, 1999). Recently, HONKOOP *et al.* (2006) conducted a statistical analysis using the same data as this paper to test for the presence or absence of along- and across-shore patterns in the sediment and benthic invertebrate characteristics. As expected, sediment grain size decreased with increasing distance from the dunes. Benthic assemblages also varied with increasing distance from the dunes, although the species compositions were highly patchy.

MIGRATORY BIRDS

Eighty-Mile Beach is a primary staging area for many migratory shorebirds on their way to and from Arctic Canada and western Siberia. Most of the migratory shorebirds found at Eighty-Mile Beach breed at high latitudes and lay their clutches of eggs in the tundra when these northern areas are free of snow and rich in food. Chicks hatch in ground nests in early July across an expansive geographical area that crosses many political boundaries, including Arctic Siberia, Mongolia, China, and Alaska (BARTER, 2002). The juveniles mature at a rapid rate because of the abundance of food found in the tundra regions at this time of year. As soon as the juvenile fledge, the adults begin their southward migration and leave their young to follow independent of the parents (WEIDENSAUL, 1999). Nonbreeding destinations can be 10,000–15,000 km from the breeding areas. On reaching maturity at 1–3 years of age, shorebirds carry out annual migrations between breeding and nonbreeding areas for the rest of their lives, which can last over 20 y (PIERSMA and PEARSON, 1999).

The birds leave the Arctic for their southward migration prior to the beginning of winter; most will leave before the end of August (PIERSMA, LAVALEYE, and PEARSON, 1999). Larger species can undertake longer legs of the migratory journey, whereas smaller species need to stop more frequently to replenish their energy reserves. There is much to be learned about the stopover portions of the journey, and tracking studies are underway (NINNES, 2001; PIERSMA, LAVALEYE, and PEARSON, 1999; SCHEIFFARTH, NEHLS, and AUSTEN, 1996; WILSON and BARTER, 1998). Migration back to the tundra normally begins in March and April and runs through May.

The feeding cycle at the nonbreeding areas such as Eighty-Mile Beach begins upon arrival because the birds' energy reserves have been depleted during the long migratory flight. Much of their plumage has changed by this time to help them blend into the intertidal mudflats (ROGERS, BATTLEY, and PIERSMA, 2000). The birds' activities during the nonbreeding period are primarily based on the tidal cycle with the birds feeding during lower tides and roosting during the high tides (ROGERS *et al.,* 2006; ROGERS, PIERSMA, and HASSEL, 2006). Prey availability is crucial to these migratory birds.

Of the 65 shorebird species recorded at the Eighty-Mile Beach, 33 are listed under international treaties designed to protect the habitat of shorebirds (PEARSON, HICKEY, and HONKOOP, 2005). By far, the most abundant migratory bird on Eighty-Mile Beach is the great knot, followed by the red knot, curlew sandpiper, red-necked stint, bar-tailed godwit, greater sand plover, and oriental plover.

The primary area of interest ranges from 10 km north of the Anna Plains Station beach entry to 60 km south. This study area is where shorebird concentrations are greatest (PIERSMA, LAVALEYE, and PEARSON, 1999; USBACK and JAMES, 1993). In October of 1998, 414,000 roosting shorebirds were counted along the shores of Eighty-Mile Beach, with the great majority occurring at the beach near Anna Plains Station, 25 to 75 km south of Cape Missiessy (PIERSMA, LAVALEYE, and PEARSON, 1999).

FIELD STUDIES

Field studies in the Eighty-Mile Beach region (Figure 1) have only recently begun. The Roebuck Bay Intertidal Benthic Mapping Programme (ROEBIM '97), conducted in April 1997, was the first extensive field study in the region that quantitatively sampled the benthic animals and sediments to evaluate the food stocks of migratory birds (PEPPING *et al.,* 1999). King Sound was the second area to be examined (DERBYM '98). The coarse sandy substrates and dominating influence of fresh water from the Fitzroy River at this site restricted establishment of any significant communities of benthic invertebrates. As a result of the lack of food, this area is not visited by many wading birds (PEARSON *et al.,* 1998). Next came the Anna Plains Benthic Invertebrate and Bird Mapping (ANNABIM '99), which both quantitatively sampled benthic organisms south of the ROEBIM site and surveyed birds in the area (CREAN, 2000; PIERSMA *et al.,* 2005). Tracking 2000 was the next study in which a number of migratory birds at Roebuck Bay were fitted with transmitters to focus on where the birds were feeding and roosting (ROGERS, BATTLEY, and PIERSMA, 2000). In 2002, the Southern Roebuck Bay Benthic Invertebrate and Bird Mapping (SROEBIM '02) once again quantitatively sampled benthic organisms as well as performing quantitative bird surveys (PIERSMA *et al.,* 2002). Most recently, the group again converged on Roebuck Bay in June 2006 to sample the northern mudflats (benthics, birds, and sediments)—the primary objective was to gather data that would permit change-over-time analyses (PIERSMA *et al.,* 2006). All of these studies are providing much needed information concerning the relationship between birds, benthos, and the habitat in which they exist.

The field data used in this project comes from the ANNABIM '99 field study. The field study team of 47 scientists and volunteers assembled at the Anna Plains Station in October 1999 to study nearly 75 km of the mudflats. The northern extent was 10 km north of the Anna Plains beach entry and the southern extent was 65 km south of the initial point (Figure 3). Each sampling area consisted of 10 to 14 transects, 200 m apart on grids running east–west or north–south. All

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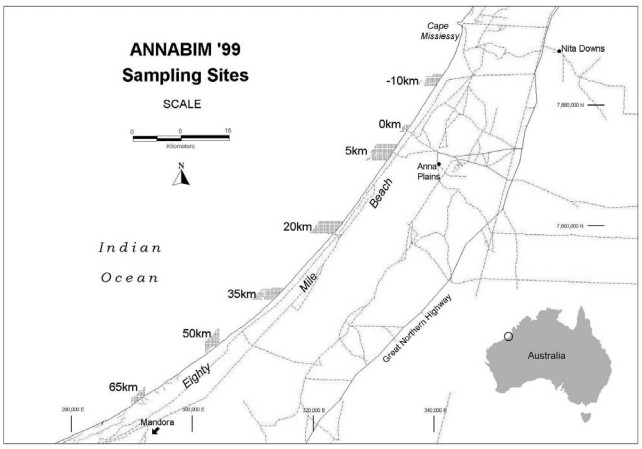


Figure 3. Study site map of Eighty-Mile Beach, including sampling sites, roads, and the location of the field camp at the Anna Plains Station (CREAN, 2000).

of the positions were linked to predetermined UTM coordinates.

Field data collection began by locating the predetermined sites with handheld GPS (at this time, selective availability was still active, and the accuracy was ±100 m). Core samples were taken with a PVC pipe (10-cm diameter) pushed down to a depth of 20 cm or the shell layer, which is the maximum depth occupied by benthos. Three cores were taken at each site and then sieved through a 1-mm mesh screen. Any remnants on the screen were labeled and saved in a plastic bag to analyze for live benthic invertebrates. In addition, a circular tube with a diameter of 4.4 cm was pushed into the ground to a depth of 10 cm. This sample was labeled and stored to be analyzed later for grain size and organic content.

Field teams also made notes regarding the nature of the sediment, depth of the oxygenated layer, and the penetrability (the depth the researchers sank into the mud) at each of the sampled areas. The presence of visible large animals such as crabs, starfish, or birds on the surface of the mudflats was also noted. Many of the field sample sites were accessible only by hovercraft because the mud was so deep in some areas that traveling to the sampling sites was not possible without transport.

The biological samples were taken back to camp and sorted in shallow plastic trays. All living animals were examined and identified under a microscope. The sediment samples were stored and later analyzed for grain size and distribution.

All the data were entered into Excel tables and combined into a single dataset that included penetrability, grain size, number of each benthic invertebrate sampled, and location. By importing this data into ArcGIS 8.3, all these data could be mapped. For this research, the attribute data was statistically analyzed to help determine patterns of benthic organism distribution throughout the mudflat, thus allowing a prediction of where the greatest number of birds may be found.

A Landsat 7 image of the study area was purchased—conveniently taken during the field study at near spring low tide. The image has a 30-m ground resolution.

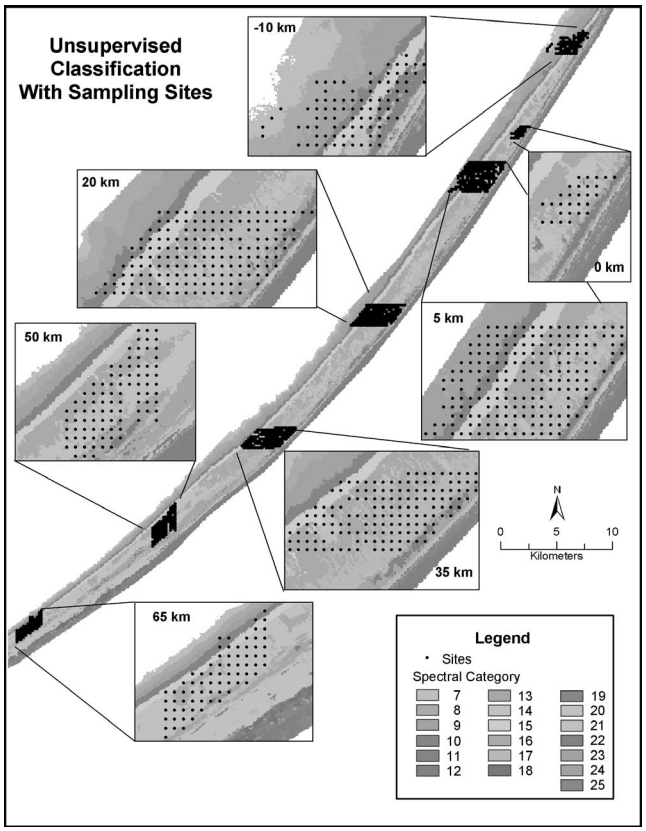


Figure 4. Results of the unsupervised classification with sample sites overlain. **For a color version of this figure, see page 684.**

IMAGE PROCESSING

The first step in this analysis was to bring the Landsat image into ERDAS Imagine software and define an area of interest (AOI)—effectively the area between the frontal dune and the ocean. By defining an AOI, the processing time required for future calculations was cut down. In addition, the unneeded spectral reflectance classes of both the ocean and inland areas were eliminated.

Next, an unsupervised classification was performed on the AOI. An unsupervised classification was chosen over a supervised classification because little was known about the variations in reflectance across the mudflats. In particular, it was impossible to define "known" classes (*i.e.,* sandy, silty, muddy, dry, *etc.*). Various numbers of classes were tested to get the best mix, but it was decided after looking at a number of classifications that 25 classes seemed to be the best choice.

Finally, the classified image was exported to an ArcInfo GRID format. The classification categories mapped in Figure 4 show the spectral categories that related to the field observation sites in the area of interest. The classification along the beach shows a roughly striated pattern as it progresses from the beach towards the water. This pattern indicates that

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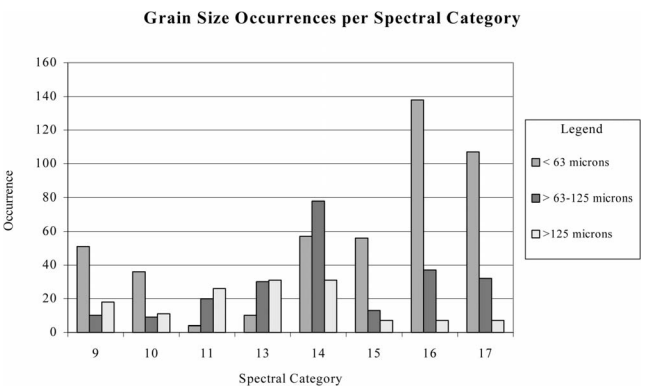


Figure 5. Chart showing the median grain size at each sample site (occurrence) per spectral category, thus illustrating the relationship between spectral category and grain size (for example, categories 16 and 17 are dominantly very fine-grained sediments). **For a color version of this figure, see page 683.**

the beach shows some degree of uniformity as it stretches from both east to west and north to south. This result demonstrated that statistically separable classes did exist, both along and across the beach. The pattern is presumed to be a function of grain size (and associated permeability or porosity) and distance from shore (which is a measure of water availability and inundation times).

To statistically compare the classified image with the field data, we merged the two datasets within ArcGIS 8.3. The classified image was in raster format; the field data were a series of points with an extensive associated attribute table. The GRIDSPOT command was used to extract the spectral category directly below each field sampling point. This value was added to a new field in the point data attribute table. Spectral categories 1–6 and 21–25 were excluded from future analyses, given that none of the field samples fell under these categories and they represented areas outside the field study such as dunes or the ocean. Sampling site −10 km was the only area that had sampling sites in categories 7 and 8. These categories (the most seaward) were sampled during the maximum spring low tide and simply were not accessible during the rest of the sampling period.

GRAIN SIZE ANALYSIS

The first analysis compared grain size with spectral categories. Median grain size samples were grouped into three categories: less than or equal to 63 μm (clay or silt), 64–125 μm (very fine sand), and 125–250 μm (fine sand). Figure 5 is a frequency plot showing the groupings of grain size values as they related to spectral categories. Simply put, spectral categories 9, 10, 15, 16, and 17 were dominantly clay or silt; 14 was dominantly very fine sand; and categories 11 and 13 were fine sand. Unfortunately, no grain size measurements were available for the sampling area at 0 km (the samples were lost).

A chi-square statistical test was used to quantify the relationship between grain size and spectral categories because

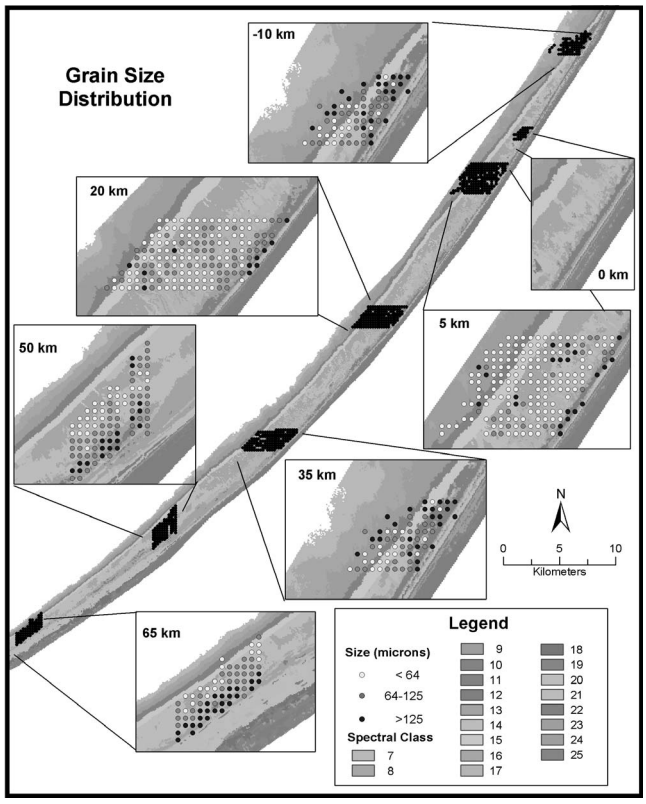


Figure 6. Map of median sediment grain size at each sample site overlain on the unsupervised classification. **For a color version of this figure, see page 684.**

the spectral category data was nominal. The overall chi-square value was computed to be 235.46. Based on 14 degrees of freedom, the critical value of chi-square was 23.68 at 5% level of significance, 29.14 at 1%, and 36.12 at 0.1%. This indicated a significant relationship. Further statistical testing resulted in an overall Cramer's V of 0.38, indicating a strong relationship between spectral reflectance categories and grain size. The details of this (and other) chi-square analyses can be found in WADE (2004).

Figure 6 displays the spatial pattern emerging from grain size samples; the coarser grained sediments tend to be closer to the beach, while the finer grained sediments are typically found closer to the ocean. Recent statistical analyses from the same data (HONKOOP *et al.,* 2006) confirm the trend that coarser sediments are generally closer to the beach and finer sediments seaward.

BENTHIC INVERTEBRATE DISTRIBUTION ANALYSIS

The next analysis compared the benthic invertebrate taxa most favored by the migratory birds to the spectral categories. The taxa included the families Capitellidae (small polychaetes), Oweniidae (tubeworms), the genus *Macrophthalmus* (sentinel crabs), and the bivalve species *Siliqua pulchella, Donax cuneatus, Macoma* cf. *exotica,* and *Tellina amboynensis.*

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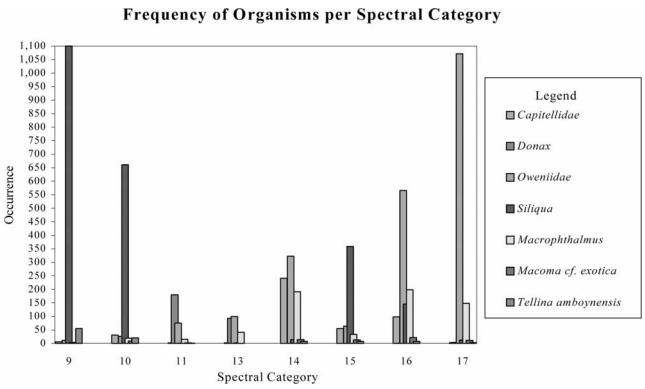


Figure 7. Chart showing the frequency of occurrence of selected benthic invertebrates at each sample site (occurrence) per spectral category, thus illustrating the relationship between spectral category and benthic invertebrates (for example, *Siliqua pulchella* dominates spectral categories 9, 10, and 15, but is rare or not present elsewhere). **For a color version of this figure, see page 683.**

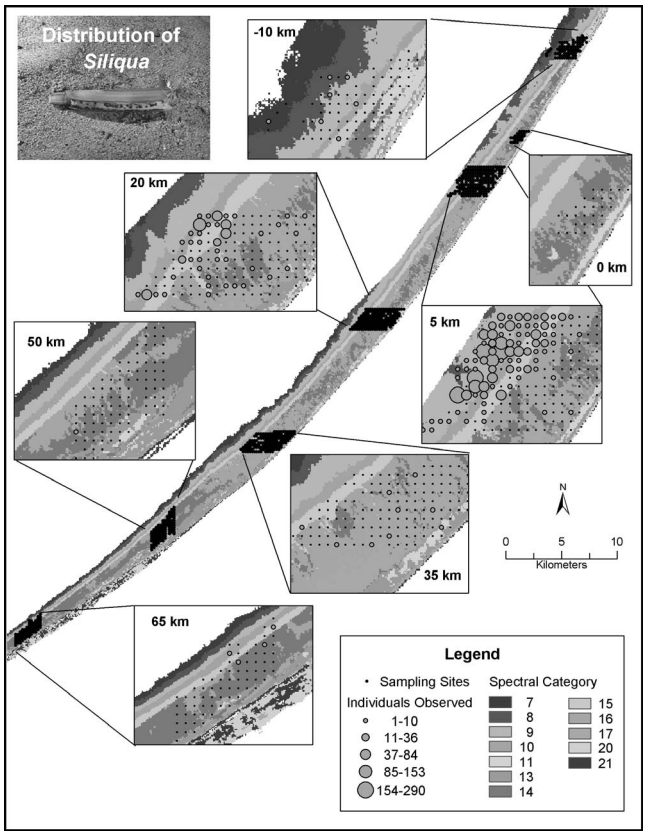


Figure 8. Map illustrating the spatial distribution of *Siliqua pulchella* at Eighty-Mile Beach. **For a color version of this figure, see page 685.**

These seven totaled nearly 6,750 of the 11,000 individuals collected at the 933 sampling sites. Figure 7 is a frequency plot showing the distribution of these taxa according to their distribution among the spectral categories. *Siliqua pulchella* and Oweniidae were, by far, the most common taxa.

As with grain size, statistical testing was used to determine that the benthic distribution was not random. The overall chi-square was 9850 with 42 degrees of freedom. The critical value of chi-square was 65.17 at 5% level of significance, 73.68 at 1%, and 84.04 at 0.1%. An overall Cramer's V of 0.49 was computed. Both scores results indicate a strong relationship between spectral classification and species distribution.

Patterns, whether positive or negative, were apparent throughout the categories. Ninety-eighty percent of *Donax cuneatus* appeared in either category 11 or 13. *Donax cuneatus* was not found at all in categories 9, 10, 14, or 15. Based on the previous results of penetrability and grain size, it is apparent that *Donax cuneatus* prefers larger grained sediments. Over 73% of Oweniidae was found in spectral categories 16 and 17, indicating a preference for the finest sediments found on the mudflats. Over half of the Capitellidae individuals preferred spectral category 14, an area where the fine sands were found. Three-quarters of *Tellina amboynensis* individuals as well as over 62% of *Siliqua pulchella* were found in spectral categories 9 and 10, predominantly silt with a mix of fine and coarse sand. *Macoma* cf. *exotica* were found more in the mixture of sands and silt. *Macrophthalmus* showed up predominately in spectral classes 14, 16, and 17, but appeared in all categories, possibly because of its greater mobility than the other species. Figures 8–14 illustrate how each of the birds' preferred food species are distributed across the study area, as well as the spectral categories in which they fall. A true pattern begins to emerge as the individual species are delineated along Eighty-Mile Beach. It is worth noting here that each map includes a photograph of a typical individual of the taxon.

Siliqua pulchella, the species that accounted for nearly half the total number of specimens of the seven benthic groups analyzed (2950 of 6726), was primarily found in spectral categories 9 (1754), 10 (661), 15 (360), and 16 (146). The majority of *Siliqua pulchella* were found at the 5- and 20-km sites, as well as closest to the low tide areas. Figure 8 illustrates the distribution of *Siliqua pulchella.* It should be noted that neap tides prevented field sampling at the southern end of the study site and at site 0, probably accounting for the lack of sampled *Siliqua pulchella* in the area.

Tellina amboynensis (Figure 9) also tended to favor the low tidal range areas, favoring spectral categories 9 (55 of the 142 individuals) and, to a lesser degree, 10. Once again, the neap tides covering the locations containing the species favored spectral categories may account for the lack of *Tellina amboynensis* found at the more southerly sites and at the sampling area at 0 km.

Capitellidae (Figure 10) showed up in the mid to low tide range with the majority of specimens collected in spectral category 14 (242 of 436). There was a very strong negative relationship (far fewer individuals found than would be expected of a random distribution) for categories 9, 11, 13, and 17.

Oweniidae specimens collected numbered 2219, nearly one-third of all benthic invertebrates analyzed. The majority was found in spectral categories 14, 16, and 17; a negative relationship was apparent for spectral categories 9 and 10. As

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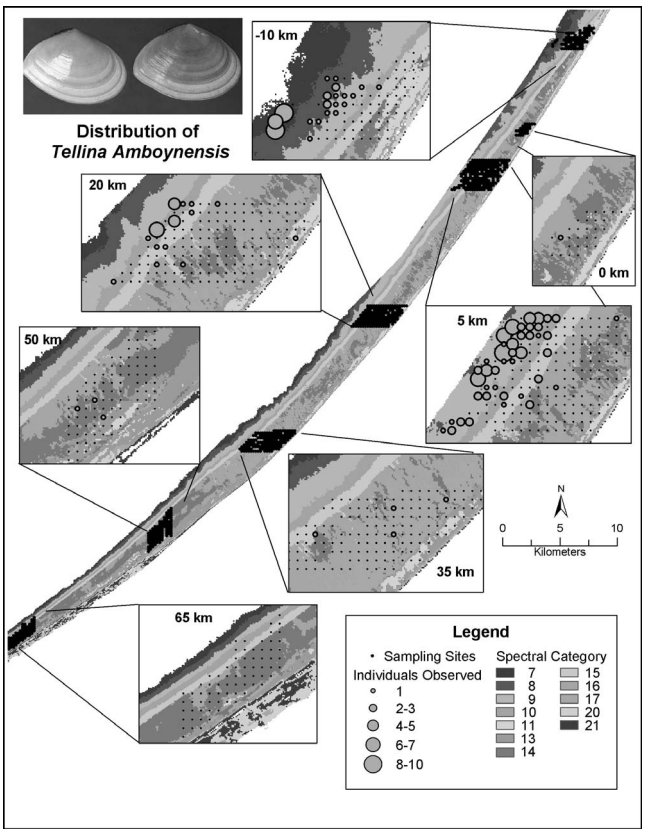


Figure 9. Map illustrating the spatial distribution of *Tellina amboynensis* at Eighty-Mile Beach. **For a color version of this figure, see page 685.**

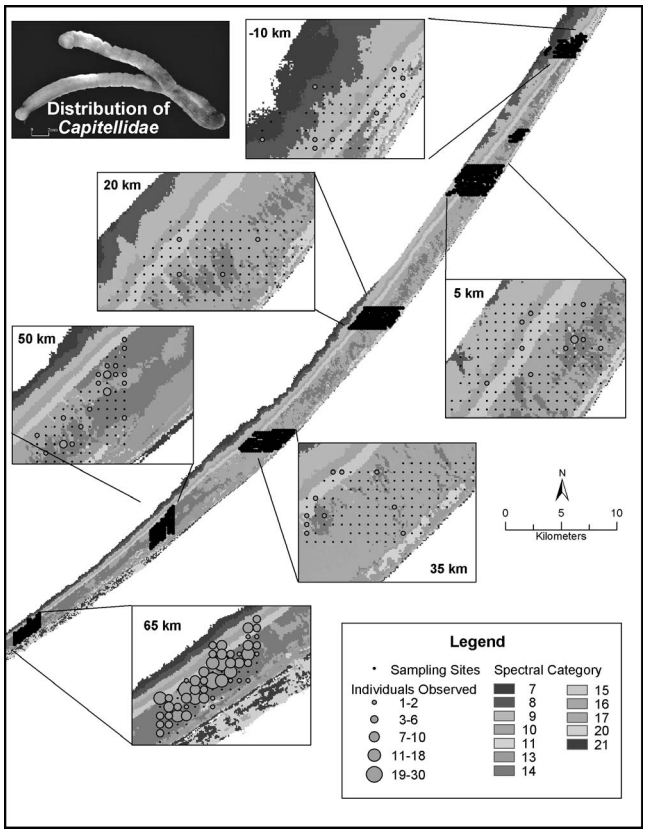


Figure 10. Map illustrating the spatial distribution of Capitellidae at Eighty-Mile Beach. **For a color version of this figure, see page 686.**

shown in Figure 11, Oweniidae favor the mid to upper tidal range.

Nearly all *Macrophthalmus* individuals were found in spectral categories 13–17. Negative relationships were apparent in 9, 10, and 11. *Macrophthalmus,* a very mobile organism that can move with the tides, was almost evenly distributed throughout the midtidal range and appeared at each of the sampling sites. Figure 12 depicts the distribution of *Macrophthalmus* found in this section of Eighty-Mile Beach.

Donax cuneatus had the simplest distribution—all were found in a very narrow strip along the high tide regions, particularly in categories 11 and 13 (Figure 13).

Macoma cf. *exotica* were found throughout the tidal ranges but in very low numbers (Figure 14). The collected benthic invertebrates of this species consisted of only 1% of the total individuals collected during the sampling session. This may account for the unpredictable spatial distribution.

Because it was assumed that grain size was a dominant factor in determining benthic distributions, a final statistical test was performed comparing benthic invertebrates and grain size. In this analysis, all species were pooled and the overall chi-square was 3369.36 with 12 degrees of freedom. The critical values were 21.03 at 5% level of significance and 32.91 at 0.1%. The Cramer's V of 0.56 was the highest computational result of this study, indicating that there is a strong relationship between benthic animal distribution and grain size.

Analyzing the various species and their distribution according to grain size gave a great deal of insight regarding certain species preferences. All but one of the *Donax cuneatus* individuals preferred areas with the large grain size (>125 μm). Nearly 90% of *Siliqua pulchella* and 64% of *Macrophthalmus* were found among the smallest grain size areas (<63 μm). Capitellidae (66%) and Oweniidae (50%) were found primarily in the 63–125 μm grain size areas. Because of the small sample sizes, sometimes because of the missing grain size data at the 0 km area, the results for *Tellina amboynensis* and *Macoma* cf. *exotica* were inconclusive. Statistical details can be found in WADE (2004).

Because there is such a strong relationship between the preference of different species to varying grain sizes sampled along Eighty-Mile Beach, and the different grain sizes show a strong relationship to specific spectral patterns, areas used by individual benthic species can be mapped all along Eighty-Mile Beach. By first predicting the benthic invertebrate distribution, different species of migratory bird feeding zones can be mapped based on benthic food preferences and distributions.

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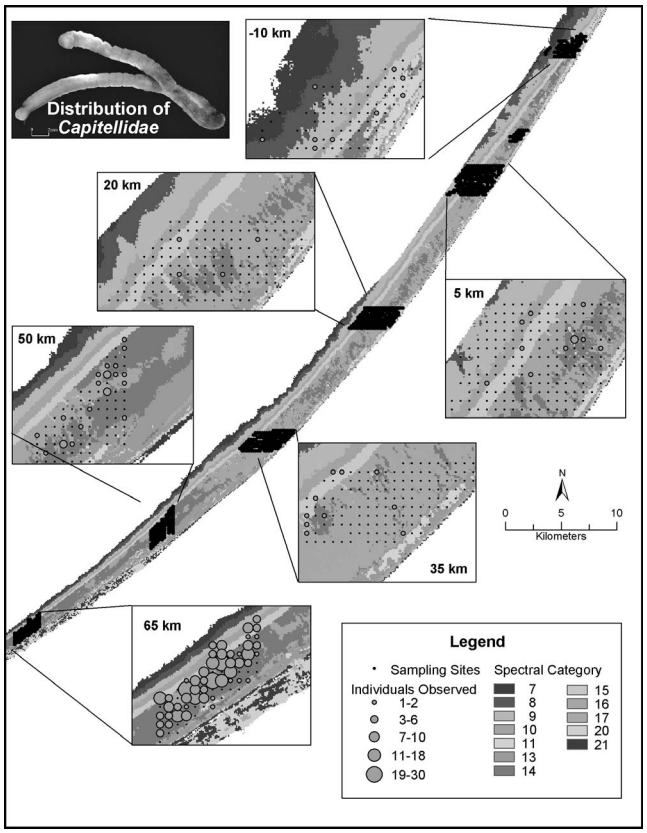


Figure 11. Map illustrating the spatial distribution of Oweniidae at Eighty-Mile Beach. **For a color version of this figure, see page 686.**

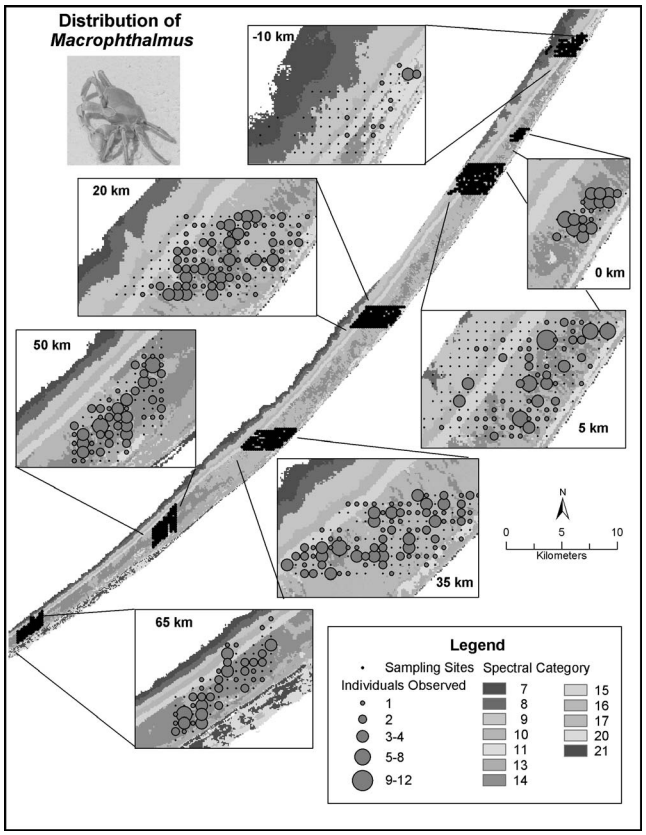


Figure 12. Map illustrating the spatial distribution of Macrophthalmus at Eighty-Mile Beach. **For a color version of this figure, see page 687.**

MAPPING BIRD FEEDING ZONES

The birds represented at Eighty-Mile Beach can be categorized based on their hunting styles (ROGERS, 2005). Many species of shorebirds have long bills with sensitive, flexible tips. They obtain food by probing their bills in the mud and extracting prey from below the surface. These hunters are further classified based on the size of the prey (macro or microbenthos). Others, such as the Terek sandpiper and red-capped plover, are visual hunters, actively sighting their prey. In the following sections, one bird species was selected from each of these three categories as an example of where they may be found on the beach based on the quantity of their favored foods. In short, the areas highlighted on the upcoming maps are those spectral categories in which that particular bird's favored food is found. The color (yellow to red) is indicative of the number of individuals found in that category. Red represents the areas (spectral categories) with the most available food; orange and yellow are areas with available food, but in lesser quantities.

Tactile Hunters of Macrobenthos

The most common shorebird on Eighty-Mile Beach is a tactile hunter of macrobenthic invertebrates, the great knot. Counts of over 160,000 of this bird alone have been recorded (ROGERS, 2005). Great knots have sensitive bills that are able to sort through various benthic prey to find their most favored food, *Siliqua pulchella.* These bivalves are swallowed whole and crushed in the birds' stomachs. In addition, the great knot favors *Tellina amboynensis* and *Macoma* cf. *exotica* (ROGERS, 2005). Figure 15 illustrates where the bird would most likely be found based on the number of favored foods found at the sampling site and the corresponding spectral category. Because so few *Macoma* cf. *exotica* were found, it was not used in the distribution map. The map indicates that great knots prefer food found in the northern region, predominantly in areas near the spring low tide line.

Tactile Hunters of Microbenthos

Tactile hunters of microbenthos are categorized as small waders. The most numerous species observed in this category was the red-necked stint. They feed by probing, jabbing, and gleaning (HIGGINS and DAVIES, 1996), usually on bare mudflats or in shallow water. The red-necked stints have a preference for foods such as Capitellidae and Oweniidae (ROGERS, 2005). These birds would most likely be found in the mid to upper tidal range based upon their favored foods (Figure 16).

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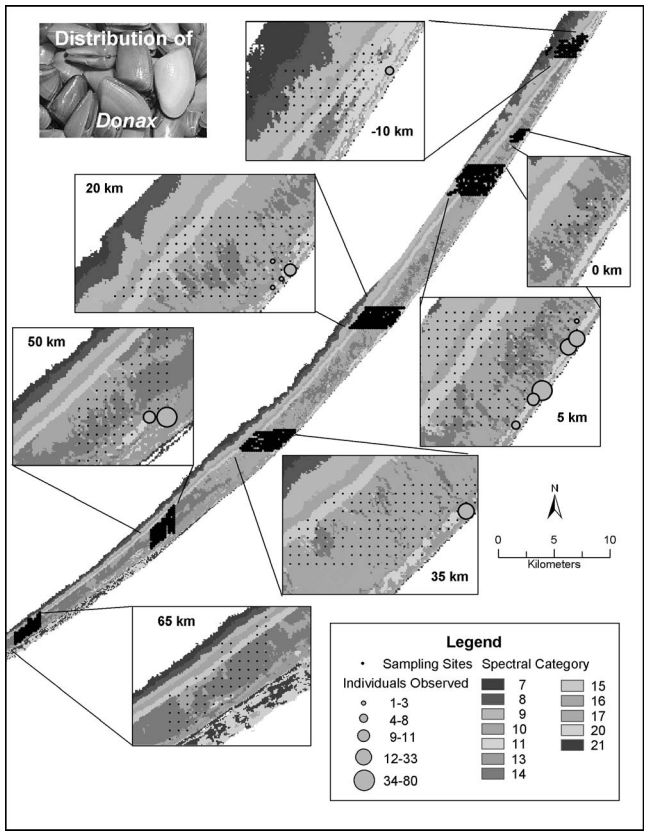


Figure 13. Map illustrating the spatial distribution of *Donax cuneatus* at Eighty-Mile Beach. **For a color version of this figure, see page 687.**

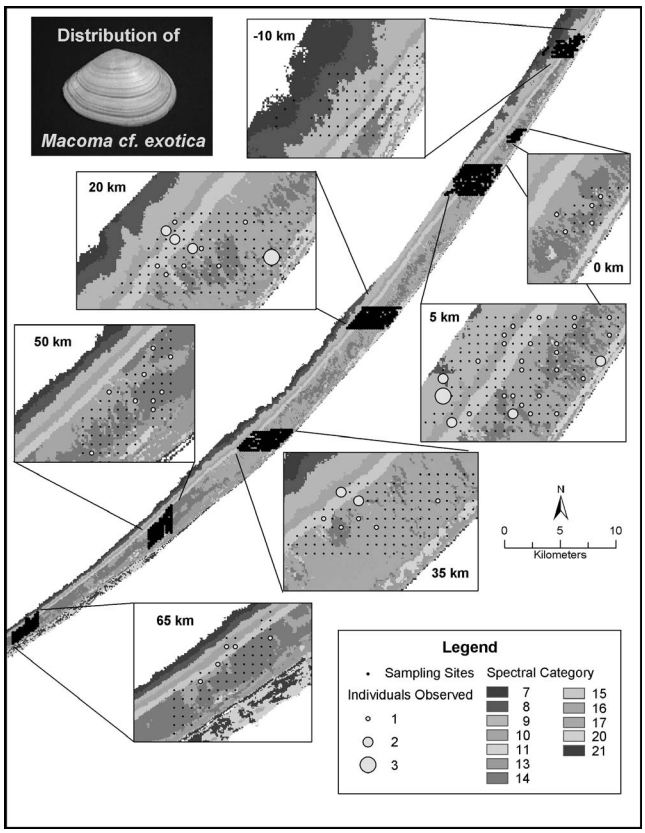


Figure 14. Map illustrating the spatial distribution of *Macoma* cf. *exotica* at Eighty-Mile Beach. **For a color version of this figure, see page 688.**

Visual Hunters of Small Active Prey

The last category studied comprises birds that hunt small active prey. The grey-tailed tattler, greater sand plover, Terek sandpiper, and red-capped plover fall into this category. Well represented on Eighty-Mile Beach, birds in this category hunt small active prey (such as small crabs) by sight.

Terek sandpipers were reasonably common on Eighty-Mile Beach and their preferred prey included *Macrophthalmus* (ROGERS, 2005). Thus, Terek sandpipers would be found in midtidal areas (Figure 17).

PROJECT LIMITATIONS

Inherent in any study are limitations. The statistical tests used were not as powerful as might be preferred. The study area was very large, and numerous field teams were used with varying degrees of skills. Loss of data and lack of information on the extended habitat of the migratory birds caused further limitations. Physical aspects, such as tidal variations limited the areas that could be sampled. Also, technological issues such as GPS accuracy and the resolution of available satellite imagery added to the limitations of this study.

The statistical techniques used were selected because the spectral category data were nominal. In addition, the logical validity of the chi-square test is greatest when the values of the expected frequencies (E) within the cells are fairly large and decreases as these values of E become smaller. Another limitation is that nonparametric tests, like chi-square and Cramer's V, are rough estimates of confidence; they accept weaker, less accurate data as input than parametric tests. This limitation can also be considered a strength because chi-square is more "forgiving" in the data it will accept, and it can be used in a wide variety of research contexts.

Further studies may be improved with more detailed grain size data. Although the three categories used indicated strong relationships with spectral categories, more detail concerning the smaller sediments would improve the analysis because it is apparent through the statistical analysis that species distribution patterns were related to differing grain sizes of sediment sampled on Eighty-Mile Beach. Also, grain size sample analysis was not available for one of the sampling sites (0 km). This resulted in an incomplete analysis for the grain size computation.

Tidal variations should be taken into consideration during field studies and the resulting analysis. Much of the mudflat area was simply unavailable for sampling because it was under water.

The GPS data collected in October 1999 isn't as accurate as one would hope. Although the area was free from overhead cover and had good satellite reception, selective availability

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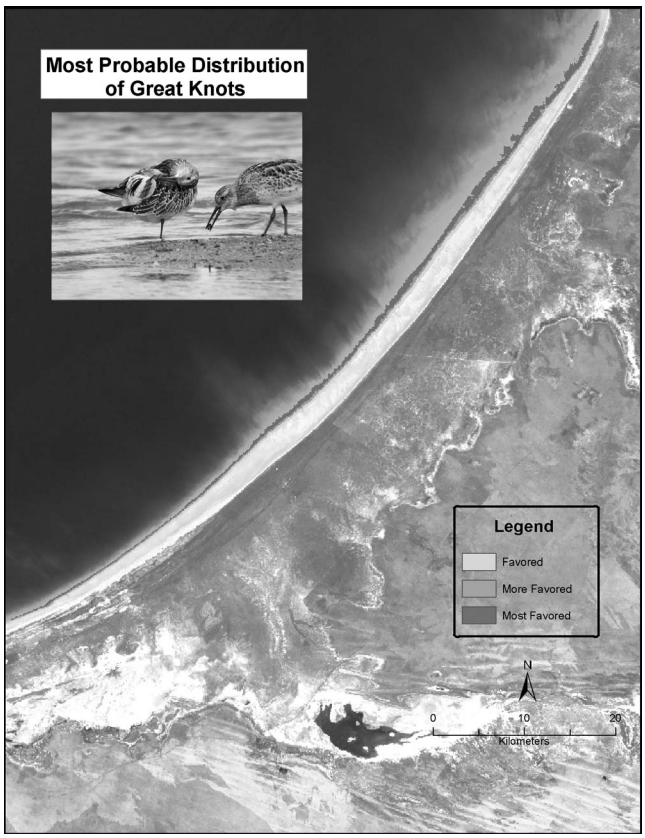


Figure 15. Map illustrating the preferential feeding areas of great knots based on benthic food preferences. **For a color version of this figure, see page 688.**

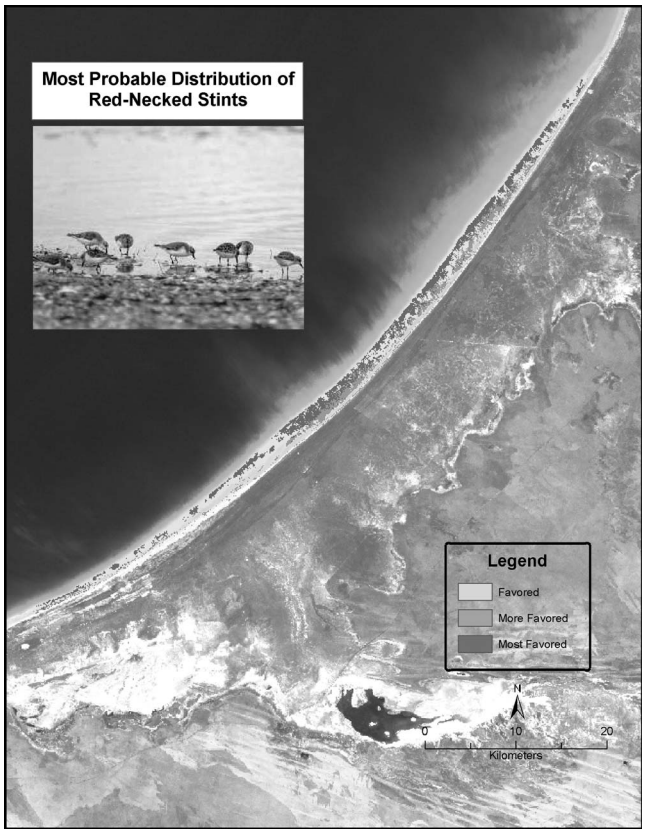


Figure 16. Map illustrating the preferential feeding areas of red-necked stints based on benthic food preferences. **For a color version of this figure, see page 689.**

had not yet been turned off, resulting in spatial accuracies of ±100 m. While real-time differential correction was available, the cost of enough receivers to provide one for each team was prohibitive. Also, sampling in thigh-deep mud wasn't the place for expensive electronics; a handheld receiver in a plastic bag was the best option.

Satellite imagery is also becoming more available at better resolutions. At the time of the analysis, imagery was expensive for this area and the best imagery for the funds available was Landsat 7 with a 30-m resolution. Future studies could take advantage of 10-m resolution SPOT (Systeme Pour l'Observation de la Terre) or higher resolution Ikonos or Quickbird imagery.

CONCLUSIONS

The primary objective of this study was to test the applicability of satellite imagery, when combined with limited field data, to map variations in the Eighty-Mile Beach mudflats as they apply to both macrobenthic invertebrates and migratory wading birds. The ultimate goal was to map feeding areas preferred by certain birds based upon the relationships between the imagery and field data.

The results of this study, as indicated in detail earlier, showed that there were statistically significant relationships between the spectral categories generated via an unsupervised classification method and both grain size and benthic invertebrate concentrations. Further, there was a statistically significant relationship between benthic invertebrate concentrations and sediment size.

Given these relationships, maps were then generated to display the particular mudflat areas favoured by the bird's preferred benthic prey. These maps, therefore, displayed the areas potentially used by particular species of migratory wading birds. This information could then be used to target management or research activities without costly and logistically difficult fieldwork.

DISCUSSION

Although there is a considerable body of literature regarding the applicability of satellite imagery to mapping terrestrial features, the literature shrinks drastically as the focus narrows to coastal, intertidal, and intertidal mudflats areas. This dearth of literature can be attributed primarily to the resolution of satellite imagery compared with the size of the intertidal area and the difficulty of acquiring imagery at just the right time. A satellite typically passes over an area about every 15 d (it varies depending on the sensor)—and having this coincide with the optimal tidal, cloud, and seasonal con-

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Figure 17. Map illustrating the preferential feeding areas of Terek sandpipers based on benthic food preferences. **For a color version of this figure, see page 689.**

ditions is very rare, and not something that can be counted upon. STELZER *et al.* (2004) did indicate good results in mapping coastal zone sediments, although few details were provided.

The focus of the coastal remote sensing literature has often been to map vegetation (*i.e.,* in salt marshes) (SCHMIDT and SKIDMORE, 2003), waterlines (CAREW and HICKEY, 2000; RYU, WON, and MIN, 2002), or topography (LOHANI and MASON, 1999; POPULUS *et al.,* 2004). When discussing mudflats, especially when attempting to relate the imagery to benthic invertebrates, the literature becomes very sparse. POMEROY and BUTLER (2005) were successful in using color infrared photography to map chlorophyll absorption from phytoplankton; however, they were unable to make any connection between the phytoplankton and the macrobenthos upon which the birds feed.

This study had two major advantages. The first was a relatively large area when compared with the 30-m pixel size of Landsat TM imagery. Second was the fortunate coincidence of a cloudfree satellite overpass during a spring low tide while we were in the field sampling. Given these conditions, a link between the imagery, sediment size, and macrobenthic distributions was established. This demonstrated the theoretical feasibility of the technique. As more and better satellites collect data, the possibility that imagery is collected under optimal conditions increases and that studies of this type become more frequent. Of course, should airborne sensors be used, the site could be imaged at the most appropriate time (RAINEY *et al.,* 2003; THOMSON *et al.,* 1998).

ACKNOWLEDGMENTS

This project, and especially all the field work, could not have been completed without considerable assistance from scientists, volunteers, and funding agencies. While an exhaustive, five-page list of people and funding agencies involved in the 1999 field work can be found in PIERSMA *et al.* (2005), we would like to especially thank Grant Pearson and Danny Rogers for assisting with drafts of this document, Pieter Honkoop for work with the sediments, Danny again for information about the birds, and the DOLA Remote Sensing Group at the Leeuwin Centre of Earth Sensing Technologies (Perth, Western Australia) for the use of the Landsat Thematic Mapper imagery.

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