Coastal Engineering 57 (2010) 203–212

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Design and performance of headland bays in Chesapeake Bay, USA

C. Scott Hardaway Jr. [a,*], James R. Gunn [b,1]

[a] Virginia Institute of Marine Science, P.O. Box 1346, Gloucester Point, VA 23062,USA
[b] Coastal Design and Construction, Inc., P.O. Box 650, Gloucester, VA 23061, USA

ARTICLE INFO

Available online 5 November 2009

Keywords:
Headland bays
Breakwaters
Chesapeake Bay
Erosion control
Pocket beach

ABSTRACT

The use of headland-breakwater systems along the shore of Chesapeake Bay began in the early 1980s. Properly designed and installed headland breakwaters with beach fill and wetlands plantings provide shore protection and create a "full" coastal profile of beach/backshore/dune which enhances habitat. They create a tertiary buffer for upland runoff and groundwater and provide access and recreation. The wetland grasses also create an erosion resistant turf. The coastal profile accommodates environmental permitting requirements of habitat enhancement for shore protection structures.

The Static Equilibrium Bay (SEB) model of Hsu and Sylvester has shown its utility in defining the pocket or embayed beach planform between headland breakwaters. Bay plots for varying wind/wave conditions and water levels define the limits of shoreline change. The embayed beach must be high and wide enough to offer protection, usually for the base of a graded upland bank, under design storm conditions. The embayed beach morphology should emulate nature; the existing beach profile should be assessed first in designing any headland-breakwater system. The design of the beach begins with establishing the minimum design beach width (B_m) and profile in the context of stable embayed beaches held by headland breakwaters. With B_m established, breakwater length (L_b), the breakwater gap (G_b) and the bay indentation distance (M_b) come into play depending on the wave environment. The empirically derived relationships between these parameters are offered as a *guide* for breakwater design along the sheltered coasts of Chesapeake Bay.

Constructing stable headland/embayed beaches for long-term shore protection can be done cost effectively. The procedures developed over the years to evaluate and design headland breakwaters have been, in retrospect, effective. These installations provide a database of successful headland-breakwater installations, some of which are over 20 years old. This database will continue to be used to verify and compare parameters for headland systems in the future as sites continue to mature.

1. Introduction

The Chesapeake Bay Estuarine System consists of a variety of shorelines that vary from low, upland banks and marshes to beaches and dunes to high bluffs. Erosion of these shorelines is significant when fetch exceeds a few kilometers and becomes severe when shorelines are exposed to fetches exceeding 16 km. Critical erosion, however, immediately threatens upland improvements and infrastructure no matter what the fetch. The use of headland breakwaters coupled with beach fill to create stable pocket or embayed beaches for shoreline management has become somewhat common place in Chesapeake Bay. Over the last 25 years, research and project installations have helped guide the way for widespread use of this technique (Hardaway and Gunn, 1991; 1999a, b; 2000; Hardaway et al., 1995; Hardaway and Byrne, 1999).

The use of headland-breakwater systems along the shore of Chesapeake Bay began in the early 1980s. Previously, shoreline erosion usually was addressed with bulkheads, groins, and stone revetments. These traditional strategies still are very much employed. These defensive means of shore protection may be effective in stopping erosion but they also "harden" the shoreline, often causing nearshore bottom scour and reducing intertidal, beach, backshore, and dune habitats. Groins can be effective if fill is added, but they tend to lose sand through time when placed along sand-limited shore reaches which are common in Chesapeake Bay.

Properly designed and installed headland breakwaters with beach fill and wetlands plantings provide shore protection and create a "full" coastal profile of beach/backshore/dune which enhances habitat. They create a tertiary buffer for upland runoff and groundwater and provide access and recreation. The wetland grasses also create an erosion resistant turf. The coastal profile accommodates environmental permitting requirements of habitat enhancement for shore protection structures.

2. Background research on design parameters

Wavelength is an important parameter in wave diffraction and refraction, both of which are important mechanisms in wave

* Corresponding author. Tel.: +1 804 684 7277.
E-mail address: hardaway@vims.edu (C.S. Hardaway).
[1] Tel.: +1 804 693 4158.

0378-3839/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.coastaleng.2009.10.007

attenuation by breakwaters and bay beach configurations. Suh and Dalrymple (1987) demonstrated that when the gap between two diffraction points (*i.e.* the ends of adjacent breakwaters) becomes approximately twice the incident wave length or more, the shoreline behind each breakwater responds independently as if there is no interaction among breakwaters. This relationship might provide the response of the tangential section of the spiral bay or pocket beach as it orients itself into the dominant direction of wave approach.

Numerous studies, as documented in Chasten et al. (1993), show that as a breakwater is lengthened relative to its distance offshore, a tombolo becomes more likely to develop. A tombolo is an essential element in headland-breakwater systems. In Chesapeake Bay projects, the tombolo must be created with the addition of an appropriate fill material since natural supply of sand generally is limited in the nearshore. As breakwater length approaches double the design wave length, it can better hold a tombolo, particularly when the breakwater acts as a headland in a multiple breakwater unit system. The level of tombolo attachment may vary from attachment above high water to a low water connection.

Bodge (1998) offers the 1/3 rule for the relationship of breakwater gap (G_b) to bay indentation (M_b) which is the maximum offset of the embayed beach from a line connecting adjacent breakwaters (*i.e.* the 1/3 rule is M_b:G_b = 1:3). Bodge (2003) provides formulae to assist in developing this ratio and notes that it is a combination of the Static Equilibrium Bay (SEB) model and his research that defines mean low water (MLW) around the embayed coast.

The Coastal Engineering Manual (CEM, 2000) terms our minimum beach (B_m) (Fig. 1) width Ymin which is defined as the minimum horizontal distance of dry beach between the mean high water (MHW) shoreline and the landward boundary or base reference line. The MHW shoreline is employed because it is a common land/water boundary shoreline on maps, it is more readily identified from aerial photos, and is a more conservative, minimum width (and volume) for shore protection. Ymin is the minimum dry beach width required to protect the foredune, cliff, structure or vegetation behind the baseline for normal storm conditions. According to the CEM (2000), the beach does the work and its resilience and recovery are critical for long-term shore protection.

Hsu and Evans (1989) and Silvester and Hsu (1993, 1997) define *dynamic equilibrium* as sand transport through an embayed coast so long as the updrift supply of sand remains constant. If the sand supply is reduced over a reasonable length of time, the bay will become more indented or will recede in the curved portion. Should the supply cease altogether, the waterline will erode back to a limiting shape which is termed *static equilibrium*. For coasts with very predominate wave climate this becomes predictable and is the basis for the SEB formula. Varying wave conditions and sand supply are the norm in Chesapeake Bay and must be accounted for in the design process. The breakwater system at Cape Henry, Virginia at the confluence of Chesapeake Bay and Atlantic Ocean illustrates how an infusion of sand, from an adjacent beach nourishment project, takes the system from static to dynamic equilibrium (Fig. 2).

Over the years, a three step process has been developed (Hardaway et al., 1995; Hardaway and Gunn, 1999a; 1999b) for practical application of this research to systems in Chesapeake Bay. The steps are: (1) assess the wind/wave climate using the computer model SMB (Kiley, 1982) which creates significant wave heights and periods from the interaction of wind over a measured fetch, (2) calculate the nearshore/nearfield wave refraction using RCPWAVE, (Ebersole et al., 1986), and (3) plot beach shore planforms using Model SEB (Hsu et al., 1989a; 1989b; Hsu and Evans, 1989). Fig. 3A and B illustrates the parameters involved in this methodology. This process is a check against the shoreline evolution assessment. If agreement is found, then there is more confidence in the site evaluation.

3. Coastal setting

The shorelines around Chesapeake Bay occupy a variety of settings. The dendritic ancestral Susquehanna River drainage is being flooded by the present oceanic transgression. The coastal boundaries are being inundated at rates of about 30 cm per 100 years, but it is the coastal storms, northeasters and the occasional hurricanes, with associated high winds and water levels that erode shorelines and transport eroded material alongshore and offshore. The patterns and rates of erosion are dictated by the coastal setting such as whether the sites are on the open bay or up the rivers or whether a site is located on a headland, a straight reach, or within an embayment. Embayed coastal settings tend to retain more sand in the nearshore than those sited on erosive headlands.

The largest storm in the entire area in the last 70 years was Hurricane Isabel which impacted Chesapeake Bay on September 18, 2003 with record high storm surge and winds. Virtually all Chesapeake Bay

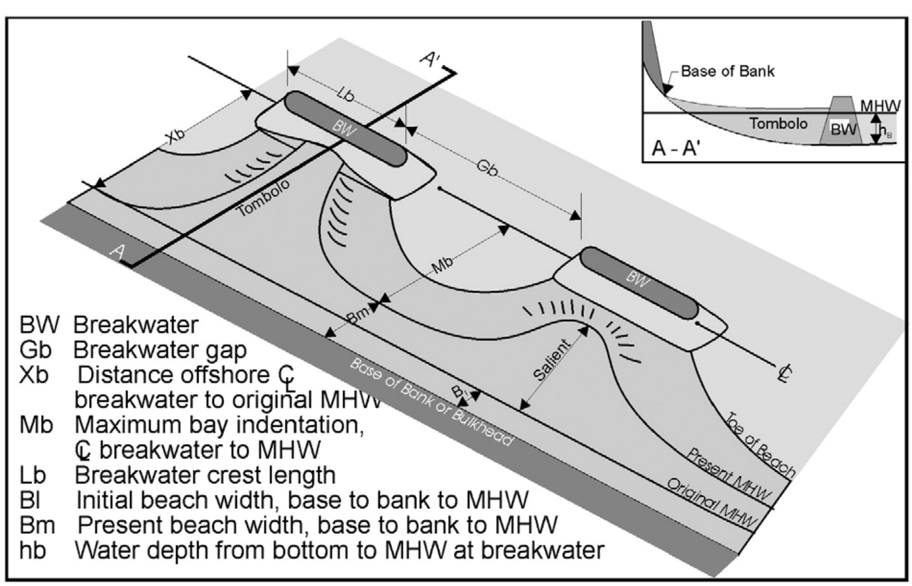

Fig. 1. Headland-breakwater system parameters.

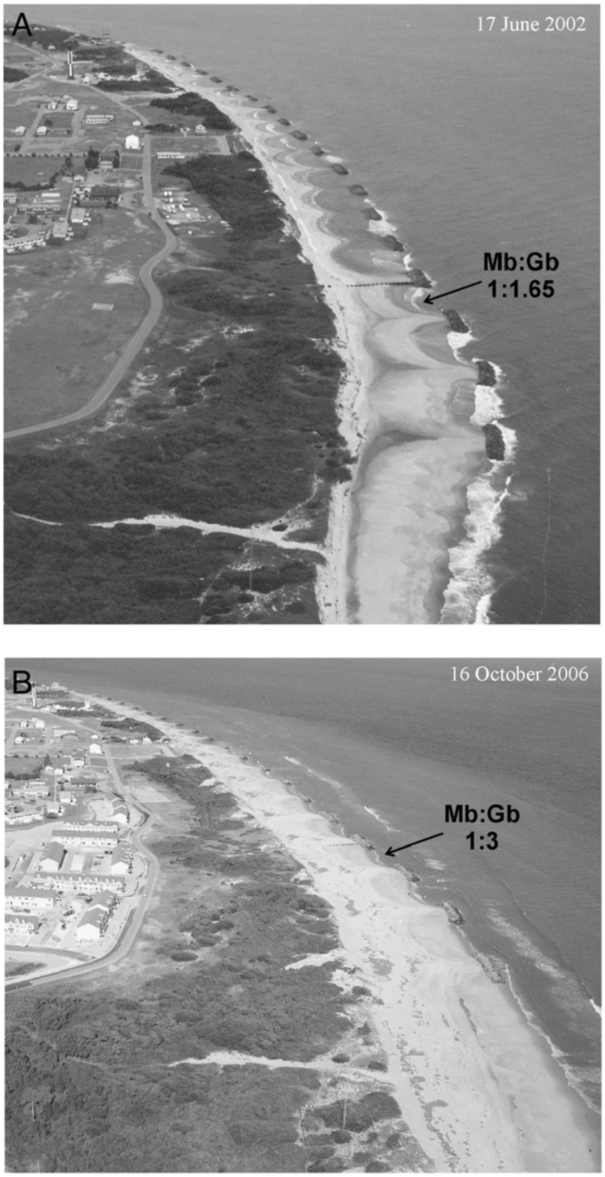

Fig. 2. Cape Henry breakwater installation showing dynamic equilibrium alongshore. M_b is the minimum beach width and G_b is the gap between adjacent breakwaters. As more sand becomes available to the system, the sight evolves to the 1/3 rule shown in B.

shorelines were affected. A Virginia Institute of Marine Science wave/current gauge in the York River showed the entire water column moving upriver at over 2.6 m/s during the height of the storm (VIMS, 2003). Peak wave height and period were 2 m and 5.1 s. Top wind speeds reached 144 km/h on a nearby anemometer. In lower Chesapeake Bay, tide gauges indicated a storm tide of +2.4 m mean lower low water (MLLW) which is about 1.5 m above normal. At Kingsmill on the James River (site #11) (Fig. 4), the tide gauge was destroyed during the storm. It stopped recording at +2 m MLLW, but surveyed trash lines and scarps at the site indicated that the maximum tide and wave level was 3.7 m above MLLW which is about 2.4 m above the mean range.

Those shorelines with open fetch to the north, northeast, east, southeast, and south were especially affected due to the rotation of Isabel's winds from north to south during her passage. Hundreds, if not thousands, of shore protection systems were damaged or destroyed. Many shorelines around the Bay which had no shore protection were eroded 3 to 9 m by storm surge and waves. Shore reaches with properly designed and constructed headland-breakwater systems incurred varying degrees of damage from none to several meters of cut at the adjacent base of the upland banks.

4. Design considerations

As with most shoreline protection projects, the local wave climate is the important hydrodynamic design element. In headland-breakwater design, the shape and performance of the embayed beach shore planform are critical in maintaining the minimum protective beach. The fetch and whether a site is exposed to a unidirectional or bimodal wind/wave field influence how the embayed beach responds to the annual and storm waves. A unidirectional wind/wave field indicates that the annual and frequent storms produce a wind/wave climate that approaches from roughly the same quadrant. Bimodal means that the annual and storm waves are from two different quadrants or that winds are from two different quadrants depending on the season.

Perhaps the most important parameters in headland-breakwater design are the width and elevation of the beach in the gaps of the breakwater system (*i.e.* minimum bay beach size). The beach must be high and wide enough to offer protection, usually for the base of a graded upland bank, under design storm conditions. Design storms are at least the 25-year event, and the breakwater itself should withstand the 100-year or greater storm. The beach morphology should emulate nature; the existing beach profile should be assessed first in designing any headland-breakwater system. The design of the beach begins with establishing the minimum design beach width (B_m) and profile in the context of stable embayed beaches held by headland breakwaters (Fig. 1). This will determine the amount of beach nourishment required. With B_m established, breakwater length (L_b), the breakwater gap (G_b) and the bay indentation distance (M_b) come into play depending on the wave environment. This paper discusses these and other minimum design parameters for shoreline protection by headland-breakwater/beach systems in fetch and depth limited settings like Chesapeake Bay.

Since the first headland-breakwater installation in 1985, the authors have attempted to address shore protection using bay beaches thereby reducing the amount of rock (*i.e.* breakwater length) per length of shoreline, accordingly. The 14 breakwater sites shown in Fig. 4 represent breakwater projects built in different coastal settings for shore protection and beach stability (Hardaway and Gunn, 2000). Stability of the bay beach is critical so that the need for future nourishment is minimized. However, rock costs for breakwater units also are significant, and it is a balance of these and project goals that make each site different.

The beach is the primary component of any given headland-breakwater system, and the source of material will dictate costs and, ultimately, the design. Sand that can be obtained directly from an adjacent sandy bank will cost significantly less than sand that has to be trucked in. All sites, except Aquia Landing, St. Catherine's Island, Carden, and Yorktown, had an eroding upland bank that the beach needed to protect from storm waves. The backshore was perched with a concrete barrier across a low shore at Aquia Landing. St. Catherine's Island and Carden were built to protect low spit features and required a backshore/dune to prevent overwash. Yorktown is a public beach with a low walkway landward of the edge of the beach.

Establishing vegetation zones within the headland-breakwater system is a critical design element since dune grasses can only survive above a stable berm along the open bay and broad rivers of the Chesapeake Bay estuarine system. Intertidal grasses must reside in sheltered regions. Beach berms occur on “natural” Chesapeake Bay beaches and typically are about 0.3 to 0.6 m above MHW. The more open the site, the higher the beach berm relative to MHW due, in part, to increased wave runup. Since a stable pocket beach is the goal of the headland-breakwater projects, it makes sense to build the beach berm into the project. Empirical evidence can be found on existing beaches, whether natural, man-induced (*i.e.* jetties) or man-made (*i.e.* groins or breakwaters). Protective beaches also may have a storm berm that

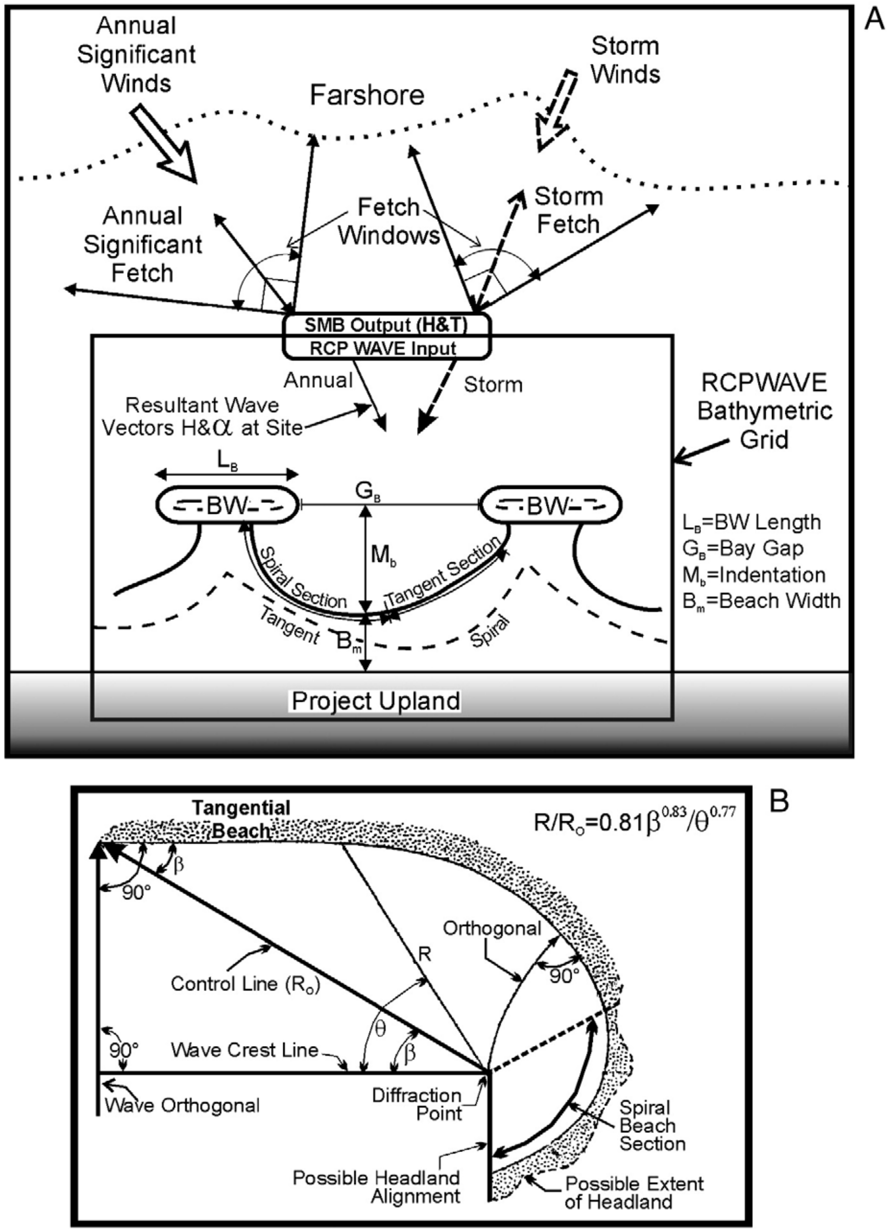

Fig. 3. Parameters related to A) wind/wave generation (SMB), nearshore wave refraction (RCPWAVE) and beach planform prediction, and B) specifically, the Static Equilibrium Bay model (after Hsu et al., 1989a,b).

is 0.3 to 0.6 m above the normal berm and 1.5 to 4.6 m landward. The berms also provide the planting zones for upper beach (*Spartina patens*) and dune grasses (*Ammophila*) (Fig. 5A and B). Often *Spartina alterniflora* can be established on the flanks of a tombolo in the lee of a breakwater unit between mean tide and spring high water.

An important consideration is how the system interfaces with adjacent shorelines. Headland breakwaters can have a significant impact on littoral processes, and those impacts need to be assessed early in the design process. Some methods range from placing shorter, low broad structures at the “downdrift” boundary to adding more fill as a feeder beach (Hardaway et al., 1993). Defining the downdrift shore is important because a bimodal wave climate may exist where storm wave conditions are different from the seasonal or annual wave field. The downdrift is more easily defined where there is a more unidirectional wave field. Bimodal and unidirectional conditions can be related to the shoreline setting or geomorphology and the location of the project on a coastal headland, embayment or a relatively straight shore (Hardaway and Gunn, 2000).

5. Equilibrium bays

The bay shoreline configuration or planform has been the topic of research for many years. The SEB model is the result of years of research by Hsu et al. (1989a,b), Hsu and Evans (1989) and Silvester and Hsu (1993, 1997) and by practical application by the present authors. In Chesapeake Bay, the waves are short, and the systems are scaled down. SEB was developed for open ocean coasts and relatively long bays between large headlands. Can the SEB be scaled down in such a manner? One must understand the goal of the project, how far off the breakwater units can or should be placed, how long the breakwater units should be, how wide the gaps should be, and, perhaps most importantly, how much beach fill is required.

The main component in SEB modeling is the position or the point of the extension of R_o, the control line (Fig. 3B). This and the tangential section of the bay are defined by the net direction of wave approach within the bay. R_o will shift with shifting wave direction, so whether a site is unidirectional or bidirectional is important. Fig. 6

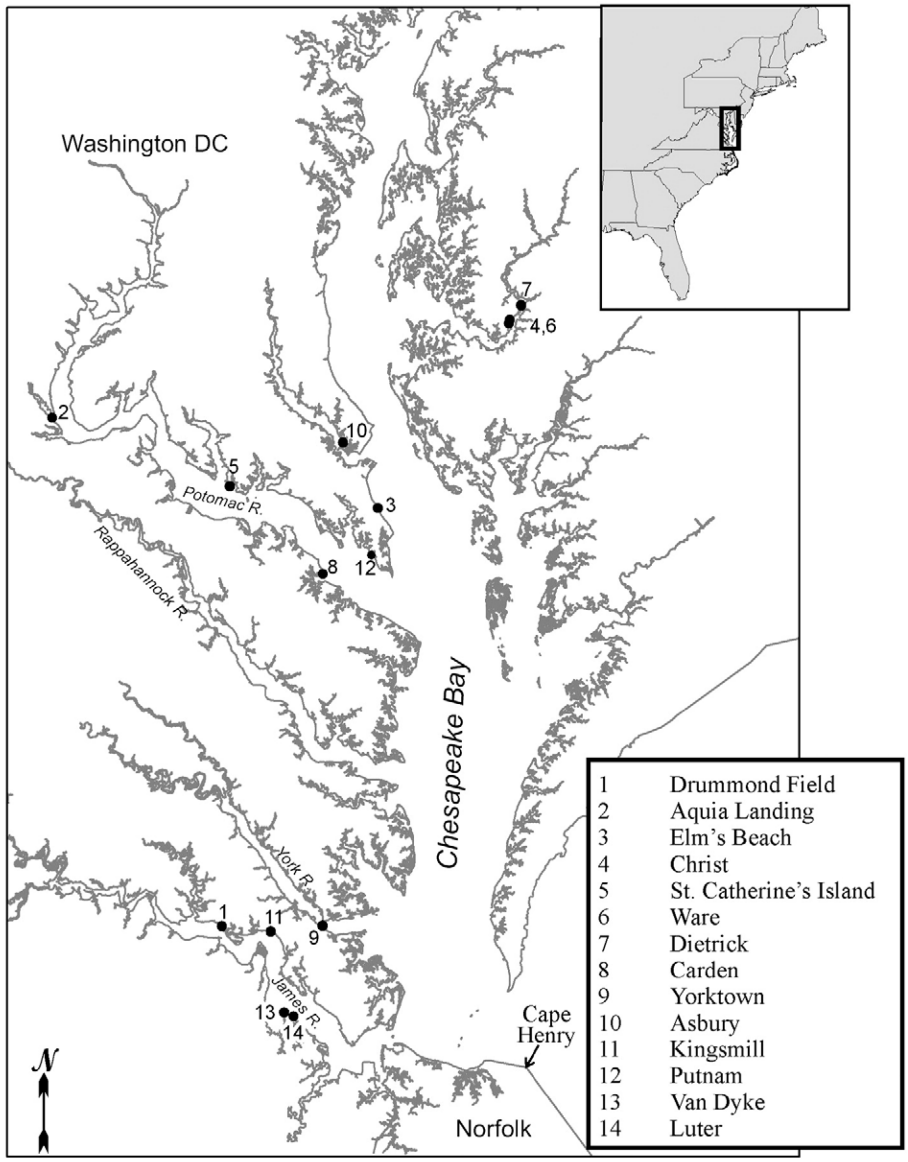

Fig. 4. Location of breakwater system installations.

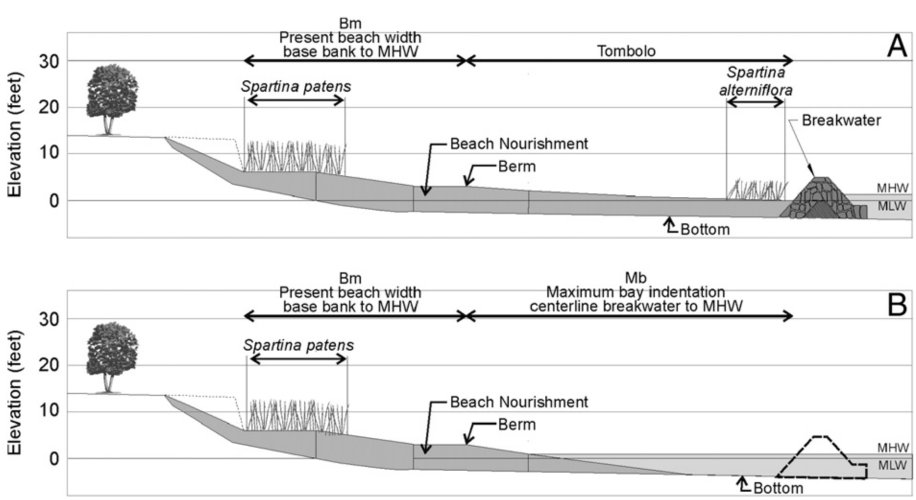

Fig. 5. Typical cross-section of A) Breakwater beach and B) Bay beach (from Hardaway and Gunn, 2000).

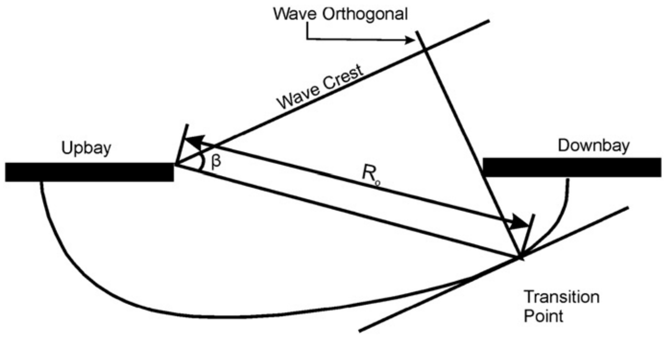

Fig. 6. Static Equilibrium Bay elements for protruding headlands (Silvester and Hsu, 1993).

shows how the wave orthogonal strikes the downdrift headland-breakwater unit and continues to a point on the bay beach shoreline that defines the terminus of R_o. This takes into account the downbay diffraction point which causes the shoreline to sit back in a small spiral. A shift in wave approach to the other quadrant would cause the small spiral to increase until it became the main spiral section of the crenulate embayment and a counter current effect would happen on the old upbay side as it became the new downbay side. This is why is it important to understand the geomorphic setting relative to the wave climate and to determine whether a site is unidirectional or bimodal or some variation therein. Also, one cannot connect breakwater units and call that R_o unless the site is in dynamic equilibrium because R_o must define the tangential section of the bay and, therefore, must be on the bay shore. The control line (R_o) can be plotted at different elevations to represent storm induced bay shapes. Typically we use the annual wave at MHW for the establishment of Ro.

The application to headland-breakwater design requires an embayment(s) to test or verify. When designing a headland-breakwater system one draws the embayments between headlands. Four bay planforms are shown in Fig. 7, and the wave orthogonal of interest is drawn in across the downbay unit and onto the shore, which for a typical or annual wave would be mean high water. The control line, R_o, is then drawn to that point from the upbay headland, β is determined, and the SEB formula applied. Table 4.2 from Silvester and Hsu (1993, 1997) can be used to get the various R values for each θ relative the associated wave crest line. One can also use the formula in Fig. 3B. In this way, the equilibrium plots allow the estimated shore planform to be "trued in".

Fig. 7 illustrates four bays drawn between two breakwater units that have different M_bs but the same wave approach. L_b and G_b also are constant. Applying the SEB formula shows how the equilibrium bay would reside against each bay "estimation". The ratios of bay indentation relative to breakwater gap (M_b:G_b) are shown as well. Bay R3 is drawn deep and might be the Kingsmill (Site 11) where a deep pocket is desired. R1 and R2 are more what we have come to see in Bay. R4 might occur where sand supplies are high (*i.e.* dynamic equilibrium). However, most bay sites need to reserve sand fill so the downdrift headland diffraction will tend to drive the shoreline back from the down bay diffraction point as seen in R1 and R2. R2 is a typical bay shape with an M_b:G_b of 1:1.65 (Hardaway and Gunn, 1991; 2000). The design beach width (B_m) will dictate bayward encroachment and embayment indentation. Some trial and error is involved. Site conditions and restrictions along with the level of protection desired will also fashion the final design.

6. Headland-breakwater performance analysis

Table 1 is a chronologic listing of selected headland-breakwater systems (Fig. 4) and their site parameters installed over the past 20 years (Hardaway and Gunn, 2000). Annual and storm wave lengths from wave climate analyses are shown. In general, as fetch increases so do the waves and wave length. The sites also are listed by wind/wave coastal settings, whether bimodal or unidirectional, in Tables 2 and 3, respectively. Site parameters of breakwater length (L_b), breakwater gap (G_b) and bay indentation (M_b) can be compared to each other by simple ratios that attempt to portray a complex system.

The project parameters (L_b), (G_b) and (M_b) (Tables 2 and 3) are averages for the project and include only those breakwaters and pocket beaches along the main trunk of the system. Interfacing breakwater units and beaches are unique to each site and comparisons would be invalid because the design beach width is not always

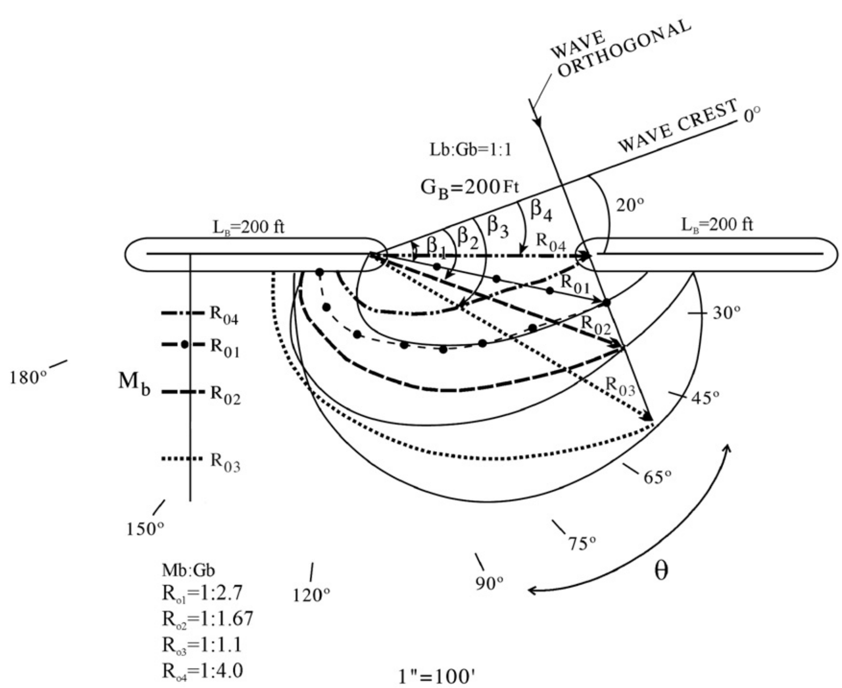

Fig. 7. Static Equilibrium embayment (dashed lines) determination for estimated shore planforms (solid lines).

Table 1
Chesapeake Bay headland-breakwater sites.

Site	Average fetch (km)	Date installed	Land use	Coast type	Wave Annual	Climate Storm
1. Drummond Field	6 to SW	Sep 1985	Residential	Embayed	$T=2.0$ $h=1.2$ $L=6.7$	$T=3.0$ sec. $h=1.8$ $L=12.8$
2. Aquia Landing	7 to E	Mar 1987	Public Beach	Headland	$T=2.0$ s $h=1.5$ $L=7.6$	$T=3.0$ s $h=2.1$ $L=13.7$
3. Elm's Beach	30 to NNE	Oct 1988	Public Beach	Straight	$T=2.5$ s $h=1.5$ $L=9.8$	$T=5.0$ s $h=2.1$ $L=22.9$
4. Christ	3 to NE	Jul 1988	Farm	Straight	$T=1.4$ s $h=0.9$ $L=4.3$	$T=2.0$ s $h=1.5$ $L=7.6$
5. St. Catherine's Island	7 to NW	Mar 1989	Spit	Headland	$T=2.0$ s $h=1.2$ $L=6.7$	$T=2.7$ s $h=1.8$ $L=11.3$
6. Ware	3 to E	Sep 1989	Residential	Embayment	$T=1.5$ s $h=0.9$ $L=4.6$	$T=2.5$ s $h=1.5$ $L=9.8$
7. Dietrick	3 to SE	Oct. 1989	Farm	Embayment	$T=1.6$ s $h=0.9$ $L=4.9$	$T=2.5$ s $h=1.5$ $L=9.8$
8. Carden	17 to NNE	Dec 1989	Spit	Headland	$T=2.0$ s $h=1.2$ $L=7.0$	$T=4.5$ s $h=1.8$ $L=18.9$
9. Yorktown	18 to NE	Sep 1994	Public Beach	Straight	$T=2.5$ s $h=1.5$ $L=9.8$	$T=4.0$ s $h=2.7$ $L=20.7$
10. Asbury	6 to NW	Dec 1995	Residential	Embayed	$T=2.0$ s $h=1.5$ $L=7.6$	$T=3.5$ s $h=2.1$ $L=15.9$
11. Kingsmill	11 to SW	Mar 1996	Residential	Embayment	$T=2.0$ s $h=1.5$ $L=7.6$	$T=3.5$ s $h=2.4$ $L=17.1$
12. Putnam	30 to SW	May 1997	Residential	Headland	$T=2.5$ s $h=0.9$ $L=7.6$	$T=4.5$ s $h=1.8$ $L=18.9$
13. Van Dyke	12 to N	Sep 1997	Residential	Headland	$T=2.0$ s $h=1.5$ $L=7.6$	$T=3.5$ s $h=2.4$ $L=17.1$
14. Luter	13 to NNE	May 1998	Farm	Straight	$T=2.0$ s $h=1.5$ $L=7.6$	$T=3.5$ s $h=2.4$ $L=15.9$

Shallow Water Wave Length ($L=(gh)^{1/2}\times T$) (From Hardaway and Gunn, 2000).
L = Wave length (meters).
h = Water depth (meters).
T = Wave period (seconds).

required. Therefore, each site is a “custom” fit within reasonable parameter relationships.

According to Hardaway and Gunn (2000) typically, breakwater systems with a bimodal wave exposure have a breakwater length to breakwater gap ratio (L_b:G_b) between 1:1.0 and 1:1.5. Van Dyke is such an example, located on a broad cape or coastal headland feature on the south shore of the James River, Isle of Wight County, Virginia (Fig. 8). When headland-breakwater systems are sited in more unidirectional settings, the L_b:G_b ratio can approach 1:1.5 to 1:2.0 particularly within embayed coastal settings that usually have an appreciable amount of natural littoral sands; for example Asbury on the Patuxent River in Calvert County, Maryland (Fig. 9). The average L_b:G_b ratios for bimodal sites are 1:1.2 whereas the average for unidirectional sites is 1:1.8.

Table 2
Chesapeake Bay beach headland-breakwater sites in bimodal wind/wave setting.

Site	Coast type	Average fetch (km)	Longest fetch (km)	L_b (m)	G_b (m)	M_b (m)	B_m (m)	L_b: G_b	M_b: G_b
6. Ware	Embayment	3 to E	4 to E	18.3	19.8	13.7	10.7	1:1	1:1.4
4. Christ	Straight	3 to NE	4 to SE	21.3	24.4	16.8	7.6	1:1.3	1:1.5
7. Dietrick	Embayment	3 to SE	4 to E	19.8	29.0	18.2	9.1	1:1.5	1:1.6
11. Kingsmill	Embayment	11 to SW	20 to S	53.3	64.0	51.8	21.3	1:1.2	1:1.2
13. Van Dyke	Headland	12 to N	22 to NNW	27.4	39.6	22.9	15.2	1:1.4	1:1.7
8. Carden	Headland	17 to NNE	43 to E	33.5	33.5	24.4	12.2	1:1.0	1:1.4
12. Putnam	Headland	30 to SW	68 to SE	33.5	42.7	42.7	18.3	1:1.3	1:1.0
3. Elm's Beach	Straight	30 to NNE	35 to SE	47.2	53.3	45.7	13.7	1:1.1	1:1.6
Average:								1:1.2	1:1.4

L_b = breakwater length (from Hardaway and Gunn, 2000).
G_b = breakwater gap.
M_b = minimum bay indentation.

Previous research by the authors has shown a relationship between the breakwater gap to pocket beach depth or indentation (G_b:M_b) ratio to be about 1:1.65 (Hardaway and Gunn, 1991). Further analysis shows that, for a unidirectional setting, the G_b:M_b ratio averages 1:1.9. For a bimodal wave climate, the average G_b:M_b ratio falls to 1:1.4.

The effectiveness of headland-breakwater sites was assessed after Hurricane Isabel (Hardaway et al., 2005) for four headland-breakwater sites: Aquia Landing, Yorktown, Kingsmill and Van Dyke. The surveys were performed as part of the Chesapeake Bay Breakwater Database and Monitoring under the U.S. Corps of Engineers Section 227 Program. Storm impacts varied at each site with the combination of storm surge and wave runup reaching +2.6 m, +3.1 m, +3.4 m, and +3.7 m MLW for Aquia Landing, Kingsmill, Van Dyke and Yorktown, respectively.

Aquia Landing and Yorktown, both public beaches, have low adjacent uplands that were readily flooded. Sand was carried into the adjacent roadways. Yorktown also had three restaurants and a hotel that were severely flooded. However, without the breakwater system damage would have been much worse since there would have been less wave attenuation and shoaling. After the storm, the sand was pushed back onto the beach and re-graded (Fig. 10). The rock structures at Aquia Landing suffered no damage and only a handful of armor stones on the Yorktown structures were turned up. These were one ton stones.

High graded banks occur along the upland coasts of Kingsmill (21 m) and Van Dyke (15 m) with significant housing on the top. The waves and storm surge attacked the base of each site's banks above the beach and backshore. Heavy established vegetation along the

Table 3
Chesapeake Bay headland-breakwater sites in unidirectional wind/wave setting.

Site	Coast type	Average fetch (km)	Longest fetch (km)	L_b (m)	G_b (m)	M_b (m)	B_m (m)	L_b:G_b	M_b:G_b
1. Drummond Field	Embayed	6 to SW	12 to S	27.4	54.9	22.9	9.1	1:2.0	1:2.4
10. Asbury	Embayed	6 to NW	13 to NW	33.5	57.9	36.6	21.3	1:1.8	1:1.7
5. St. Catherine's Island	Headland	7 to NW	15 to W	30.5	29.0	21.3	21.3	1:1*	1:1.4*
2. Aquia Landing	Headland	7 to E	9 to NE	33.5	48.8	19.8	18.3	1:1.5	1:2.5
14. Luter	Straight	13 to NNE	23 to NNW	29.0	48.8	30.5	15.2	1:1.7	1:1.6
9. Yorktown	Straight	18 to NE	43 to E	49.0	91.4	51.8	15.2	1:1.8	1:1.8
Average								1:1.8	1:1.9

* the use of dredge material required a more conservative design.
L_b = breakwater length (from Hardaway and Gunn, 2000).
G_b = breakwater gap.
M_b = minimum bay indentation.

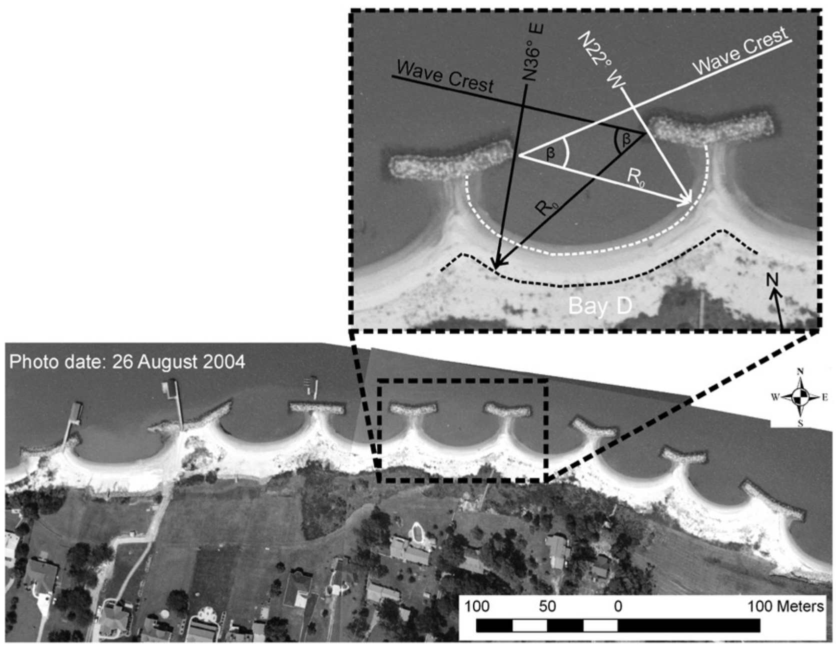

Fig. 8. Van Dyke shoreline showing the annual and storm wave direction and approximate shoreline resulting from that wave.

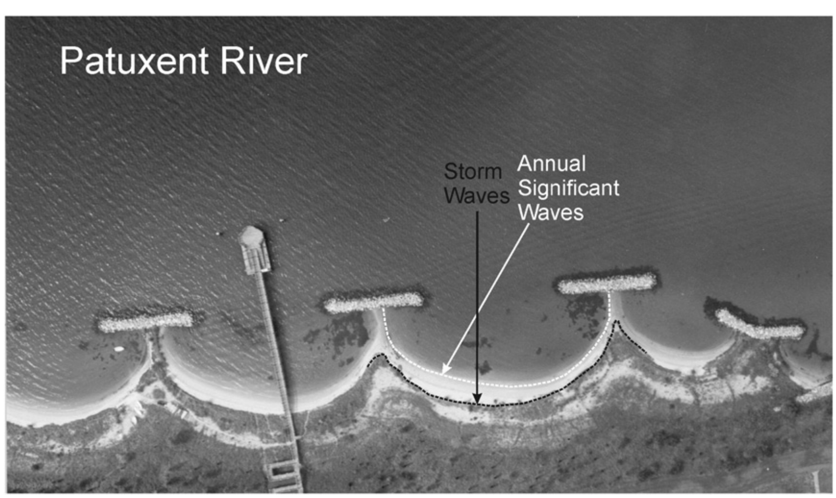

Fig. 9. Asbury project located in a coastal embayment with a unidirectional wind/wave climate demonstrating shore planforms resulting from annual and storm waves which approach from the same quadrant. Photo date: 20 Oct 2005.

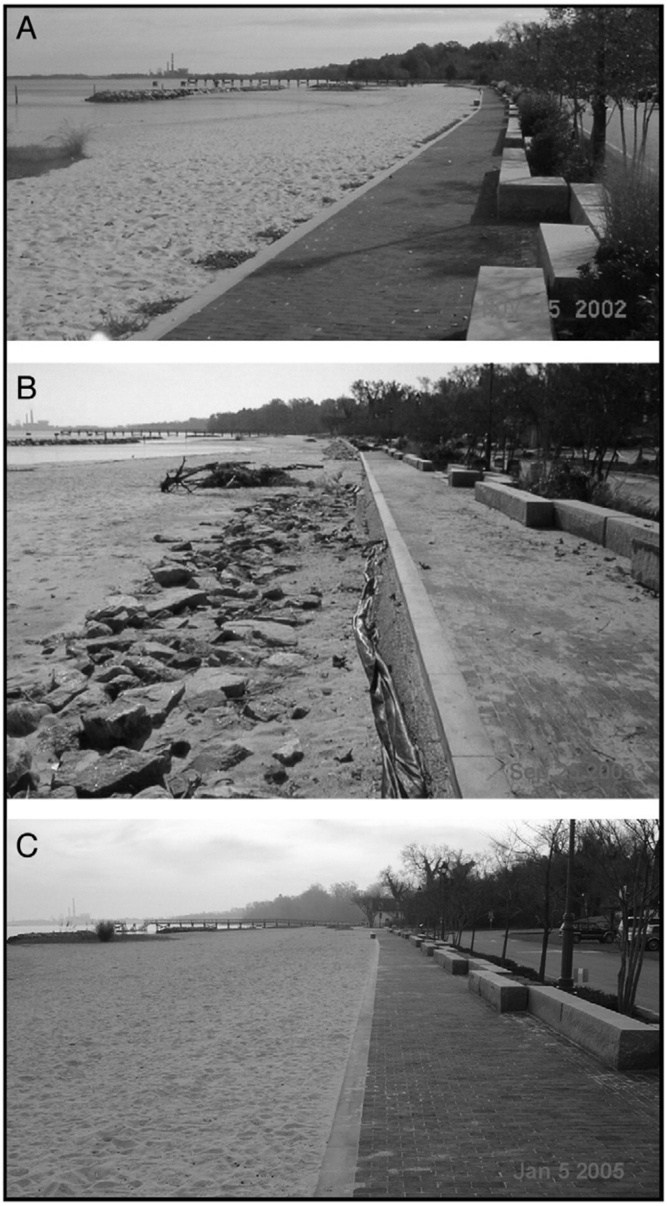

Fig. 10. View along the upriver portion of Water Street, Yorktown, Virginia (site #9), at the main recreational area A) before Hurricane Isabel, B) immediately after Isabel, and C) after the beach was repaired.

Kingsmill back base allowed only minor back scarping by wave action which was confined to the embayments. Van Dyke suffered significant bank erosion, particularly in the embayments and against the 2:1 graded bank face but this did not threaten the integrity of the bank slope. Areas along the Van Dyke site with graded banks at a 3:1 graded had little or no scarping. This supports the process by which a low broad stable beach planform is very effective at storm wave attenuation (Fig. 11). Fig. 11 also shows a 3:1 bank next to a stone revetment with a crest elevation at +2.4 m MLW.

7. Conclusions

The Static Equilibrium Bay (SEB) model of Hsu and Evans (1989) and Silvester and Hsu (1993; 1997) has shown its utility in defining the pocket or embayed beach planform between headland breakwaters. Bay plots for varying wind/wave conditions and water levels define the limits of shoreline change for each scenario, particularly conditions other than true unidirectional.

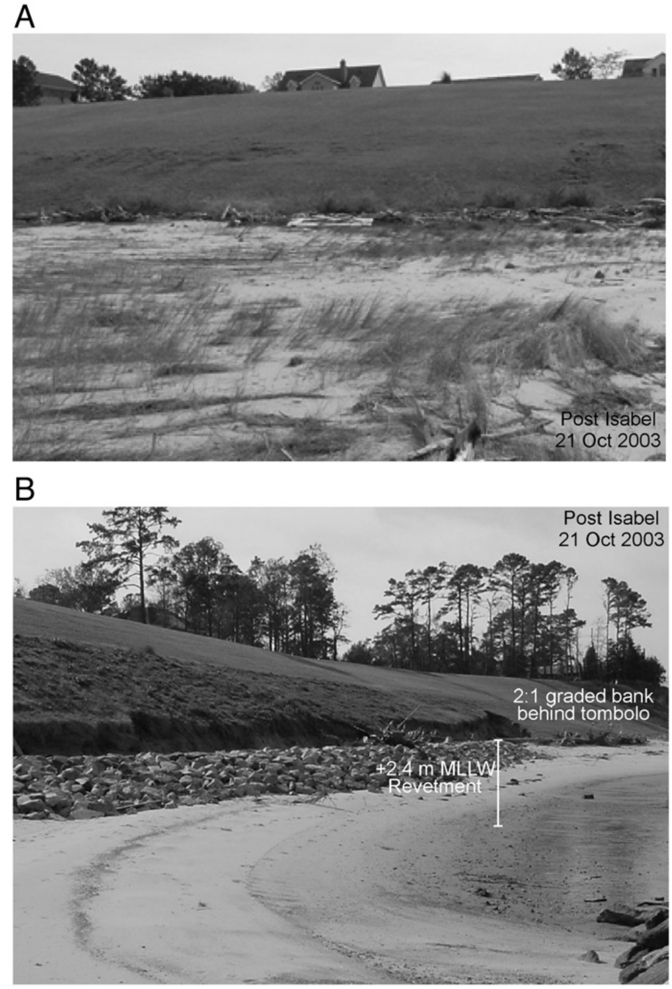

Fig. 11. Impact of Hurricane Isabel at Van Dyke including A) the upriver end where the bank is graded at 4:1, and B) at the downriver end of Van Dyke where the shore is protected by a revetment.

Generally, projects located in bimodal wind/wave settings should allow for what can be called omnidirectional wave attack at varying water levels. The breakwater gap (G_b) may have to be reduced relative to both breakwater length (L_b) and pocket beach indentation (M_b) so that major shifts in the beach planform will adjust within the embayment. On sites with a definite unidirectional wind/wave approach, the breakwater gap (G_b) can be opened relative to L_b and M_b. Some M_b:G_b ratios are as high as 1:2.5, and the tangential feature of the pocket beach does not change significantly alongshore. The sand volume, the protective beach, required to be placed in headland-breakwater systems is determined by the breakwater system dimensions that fall within the boundaries of the aforementioned parameter relationships (Hardaway and Gunn, 2000).

The parameter relationships are offered as a *guide* for breakwater design along fetch and depth limited shorelines like the Chesapeake Bay. These headland-breakwater systems have and continue to provide long-term shore protection, but they also create a stable coastal profile of beach, backshore, and low dunes that provide wetlands habitat and easy access to the waters of Chesapeake Bay. Constructing stable pocket beaches for long-term shore protection can be done cost effectively. The procedures used over the years to evaluate and design headland breakwaters have been, in retrospect, effective. These installations provide a database of successful headland-breakwater installations, some of which are over 20 years old. This database will continue to be used to verify and compare parameters for headland systems in the future as sites continue to mature.

References

Bodge, K.R., 1998. Beach fill stabilization with tune structures: experience in the southeastern USA and Caribbean. In: Allsop, N.H.W. (Ed.), Coastlines, Structures and Breakwaters. Thomas Telford, London, pp. 82–93.

Bodge, K.R., 2003. Design aspects of groins and jetties. Advances in Coastal Structure Design. ASCE.

CEM, 2000. Coastal Engineering Manual. Veritech, Inc., Vicksburg, MS, USA.

Chasten, M.A., Rosati, J.D., McCormick, J.W., 1993. Engineering design guidance for detached breakwaters as shoreline stabilization structures. Tech. Report CERC-93-19, U.S. Army Corps of Engineers, Waterways Experiment Station, MS.

Ebersole, B.A., Cialone, M.A., Prater, M.D., 1986. RCPWAVE—A linear wave propagation model for engineering use. Tech. Report CERC-86-4, U.S. Army Corps of Engineers, Waterways Experiment Station, MS.

Hardaway, Jr. C.S., Byrne, R.J., 1999. Shoreline management in Chesapeake Bay. Special report in Applied Marine Science and Ocean Engineering No. 356, Virginia Institute of Marine Science, College of William & Mary, VA, USA.

Hardaway Jr., C.S., Gunn, J.R., 1991. Headland breakwaters in the Chesapeake Bay. Proceedings Coastal Zone '91, ASCE 2, 1267–1281.

Hardaway Jr., C.S., Gunn, J.R., 1999a. Chesapeake Bay: design, installation, and early performance of four (4) new headland breakwater/composite systems. Beach Preservation Technology 1998. Florida Shore and Beach Preservation Assoc., pp. 1–18.

Hardaway Jr., C.S., Gunn, J.R., 1999b. Chesapeake Bay: design and early performance of three headland breakwater systems. Proceedings Coastal Sediments '99. ASCE, pp. 828–843.

Hardaway Jr., C.S., Gunn, J.R., 2000. Shoreline protection: design guidelines for pocket beaches in Chesapeake Bay, USA. Proceedings Carbonate Beaches.

Hardaway Jr., C.S., Gunn, J.R., Reynolds, R.N., 1993. Breakwater design in the Chesapeake Bay: dealing with the end effects. Coastal Engineering Considerations in Coastal Zone Management, Proceedings Coastal Zone '93. American Shore and Beach Preservation Association/ASCE, pp. 27–41.

Hardaway Jr., C.S., Gunn, J.R., Reynolds, R.N., 1995. Headland breakwater performance in Chesapeake Bay. Proceedings 1995 National Conference on Beach Preservation and Technology, St. Petersburg, FL, pp. 365–382.

Hardaway Jr., C.S., Milligan, D.A., Wilcox, C.A., Meneghini, L.M., Thomas, G.R., Comer, T.R., 2005. The Chesapeake Bay breakwater database project: Hurricane Isabel impacts to four breakwater systems. Virginia Institute of Marine Science, College of William & Mary, VA, USA.

Hsu, J.R.C., Evans, C., 1989. Parabolic bay shapes and applications. Proceedings Institution Civil Engineers, Part 2. Thomas Telford, London, 87, 557–570.

Hsu, J.R.C., Silvester, R., Xia, Y.M., 1989a. Generalities on static equilibrium bays. Coastal Engineering 12, 353–369.

Hsu, J.R.C., Silvester, R., Xia, Y.M., 1989b. Generalities on static equilibrium bays: new relationships. Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE 115 (3), 285–298.

Kiley, K., 1982. A shallow water wind wave prediction program. Based on U.S. Army Corps of Engineers Program developed by CERC, Fort Belvoir, Virginia.

Silvester, R., Hsu, J.R.C., 1993. Coastal Stabilization: Innovative Concepts. Prentice-Hall, Englewood Cliffs, NJ. 578 pp.

Silvester, R., Hsu, J.R.C., 1997. Coastal Stabilization. World Scientific Publ. Co., Singapore. 578 pp. (Reprint of Silvester and Hsu, 1993).

Suh, K.D., Dalrymple, R.A., 1987. Offshore breakwaters in laboratory and field. Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE 113 (2), 105–121.

VIMS, 2003. VIMS scientists quantify Isabel's impacts on the Bay. Press Release, Virginia Institute of Marine Science, College of William & Mary, VA, USA. http://www.vims.edu/newsmedia/press_release/isabel.html.