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Sheldon Marsh – Section 227 Demonstration Project – Physical Model Study[1]

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) summarizes the effectiveness of a wide-crested, submerged, dimensioned, rubble-mound breakwater matrix based on physical model testing conducted at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. The shore protection concept was designed as an innovative alternative to traditional rubble-mound breakwaters for the purpose of shoreline stability at the National Shoreline Erosion Control Development and Demonstration (Section 227) Program's Sheldon Marsh demonstration project location.

LOCATION: The proposed restoration area is located along the eroding portion of the barrier beach, which protects Sheldon Marsh State Nature Preserve. The preserve is located on the southwestern shore of Lake Erie, west of the city of Lorain, OH (Figure 1). The marsh consists of a 1.8-km- (1.12-mile-) long barrier beach and wetland preserve located at the southeast end of the 10.5-km- (6.52-mile-) long Cedar Point sand spit in Huron, OH (Figure 2).

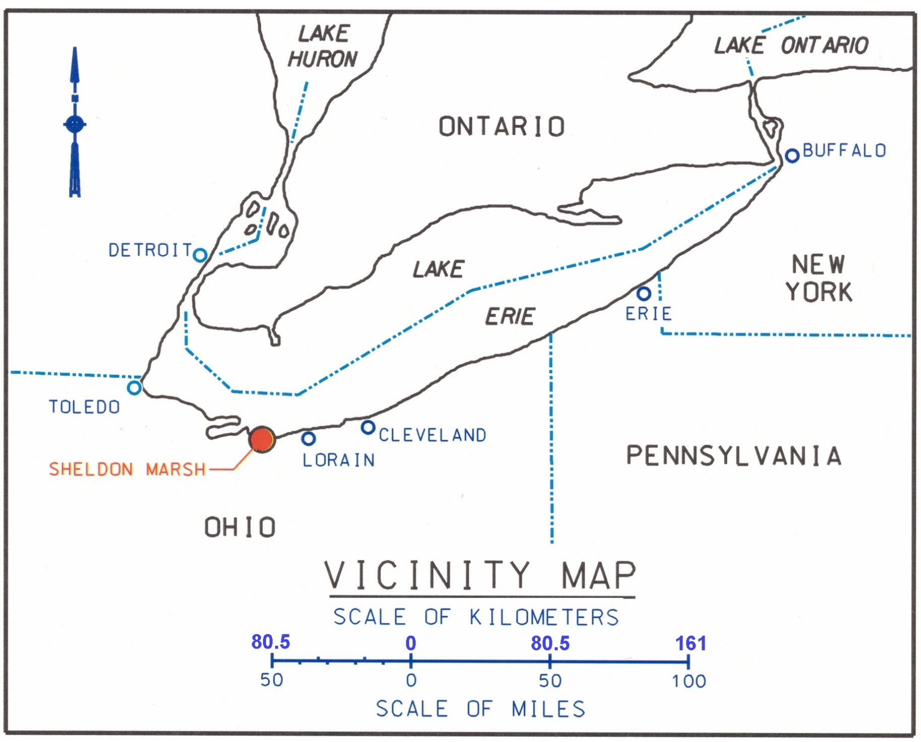

Figure 1. Vicinity map

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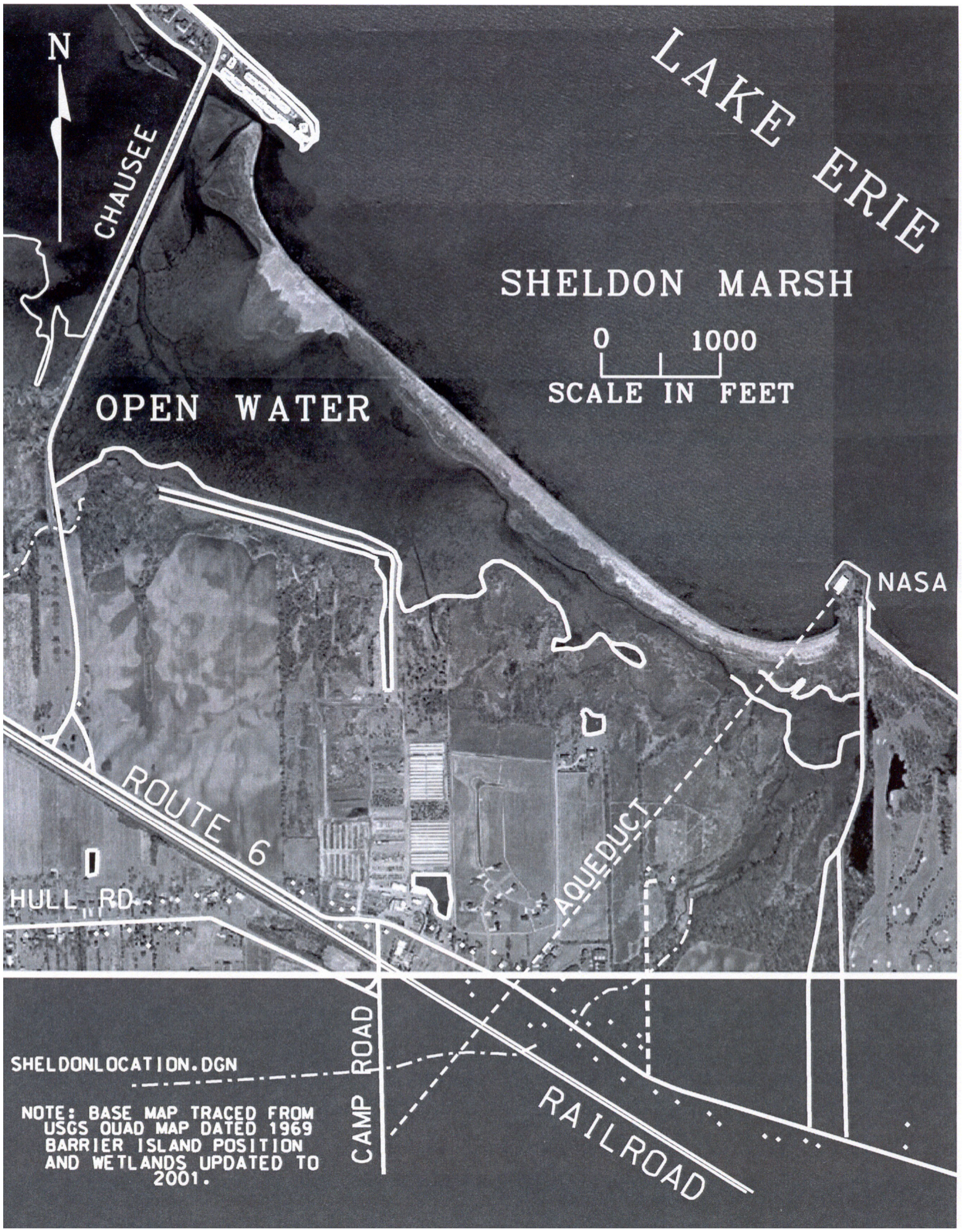

Figure 2. Sheldon Marsh Nature Preserve project location map

BACKGROUND: Sheldon Marsh is one of only a few remaining Lake Erie natural coastal wetlands not restricted by man-made structures for water level management. The marsh contains many types of habitat such as old-field, hardwood forest, woodland swamp, cattail marsh, barrier sand beach, and open-water lake (ODNR 2005). Barrier beach restoration is essential to the survival of these plant and animal communities in this rare marsh setting.

In the nearshore zone the lake bed consists of a patchy sand layer above a clay and peat base. There are currently no shore protection structures located on or near the barrier. However, stone seawalls protect a National Aeronautics and Space Administration (NASA) pump station at the east end of this site, and an armored condominium development just west of the site (Figure 2) creates a headland. Approximately 300 m (1,000 ft) offshore of the beach are timber pilings and remnants of a roadbed that once extended from the pump station to the western end of Cedar Point. The remaining portion of the old roadbed sporadically rises less than a meter above the present lake bed. The present barrier beach rises 2.1 to 2.4 m (6.9 to 8 ft) above Low Water Datum (LWD)[1] and is composed of medium to coarse sand (Figure 3).

Figure 3. Looking east along barrier beach, 2001

GEOLOGIC BACKGROUND AND BARRIER RETREAT: Pleistocene glacial drift underlies modern sediments in Sandusky Bay and other shallow areas at the west end of Lake Erie. The Cedar Point Peninsula formed about 12,000 years ago as lake levels gradually rose to their present levels following retreat of the continental glaciers northward beyond the Niagara Escarpment. Large quantities of sediment supplied by rivers and eroding bluffs along the south shore of Lake Erie formed a spit and bay mouth bar across Sandusky Bay. The spit was

[1] All elevations (el) cited in this note are referenced to Low Water Datum (LWD) in feet. To convert feet to meters, multiply number of feet by 0.3048. LWD is defined as 569.2 ft (International Great Lakes Datum).

probably stable or growing geomorphic feature before the mid-1800s, when settlement of Ohio and industrialization caused profound changes to the coastal sediment regime. Numerous factors contributed to a reduction of the littoral sediment. As towns grew along the shore, attempts were made to armor bluffs and prevent their erosion. This reduced the supply of sediment formerly derived from eroding bluffs. Jetties at river mouths, such as the ones at the Huron River, blocked the littoral sediment transport. Material dredged from the mouths of harbors was typically deposited in deep water or on land, further depriving the lacustrine environment of sediment. Countering this trend, it is likely that the sediment load of rivers increased as forests were cut down and the land was converted to farming. However, much of this sediment may not have entered the littoral system because of river-mouth jetties and dredging of harbor entrances.

By the early part of the 20th century, the sand spit along Sheldon Marsh was retreating southward. The mechanism was similar to the classic overwash process that occurs at barrier islands on ocean coasts around the world. However, the retreat process at Sheldon Marsh is somewhat different because on ocean coasts, the average water level only varies slightly over periods of centuries, while the Great Lakes experience fluctuating water level on irregular cycles of years or decades (Headquarters, U.S. Army Corps of Engineers 1995).

On a Great Lakes barrier, when water level is high (as in the mid-1980s), the maximum relief may be less than 30 cm (1 ft), and the beach is subject to washover or breaching during storms. If overwashed, sand is carried across the barrier and deposited into the lagoon on the landward side in the form of broad sheets. If the barrier is breached, sand is carried into the lagoon through the channels and deposited in the form of fans. Trees on the barrier are toppled, and frequent overwash prevents plants from being reestablished. When the lake level drops, winds rework the barrier, forming dunes. Vegetation becomes reestablished and helps stabilize the barrier against further erosion until the lake level rises again. The result is that barrier retreat (barring man-made influences) is an irregular process, with stability during low lake level and rapid retreat during high water.

Bray (1988) documented how the barrier beach at Sheldon's Marsh retreated between 1937 and 1968. The beach originally extended westward from the end of the road, now the NASA Plum Brook water intake pump station, to Cedar Point (Figure 4). Outside of the nature preserve, most of the Cedar Point spit was privately or commercially owned and fronted by rock shore protection structures, which anchored the position of the shoreline. But at Sheldon Marsh, the beach was provided only minor protection by the deteriorating asphalt roadbed, and over time, the overall feature became narrower as sand was lost from the system.

In November 1972, a rise in lake level coupled with a major northeast storm caused several 15-m (50-ft) breaches in the northwest end of the barrier. This separated the remaining (eastern) portion of the barrier from the Cedar Point spit (Figure 5).

Over the following 30 years, the remaining beach migrated westward and shoreward approximately 370 m (1,200 ft), forming a broad U-shaped bay (Figure 6).

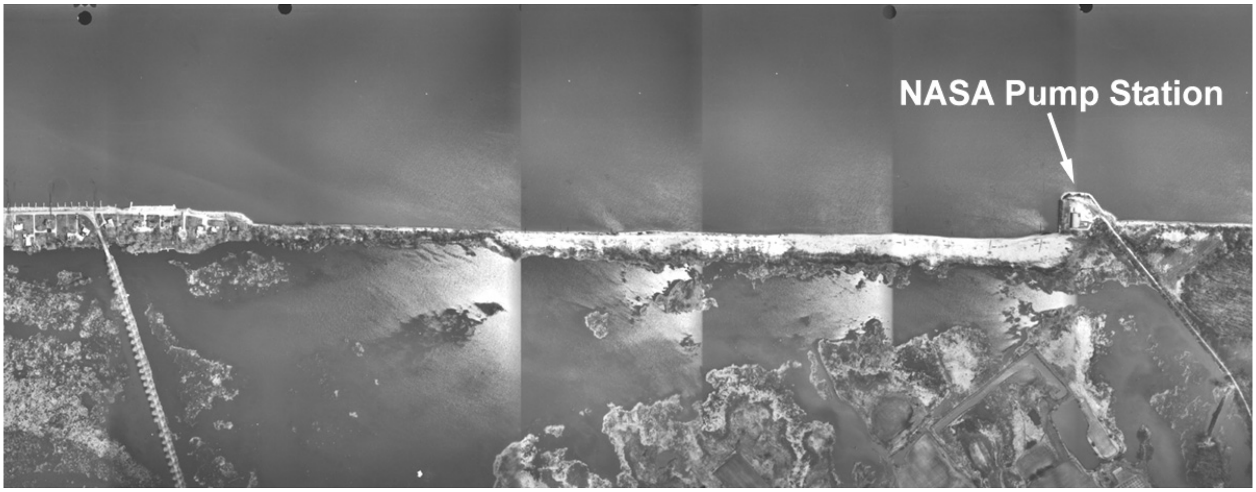

Figure 4. 1968 aerial photograph illustrating barrier island (North is to the top)

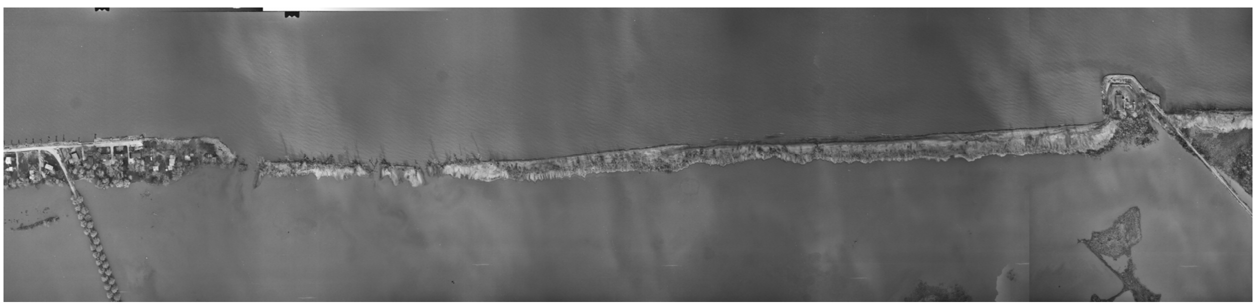

Figure 5. 1972 aerial photograph illustrating barrier island

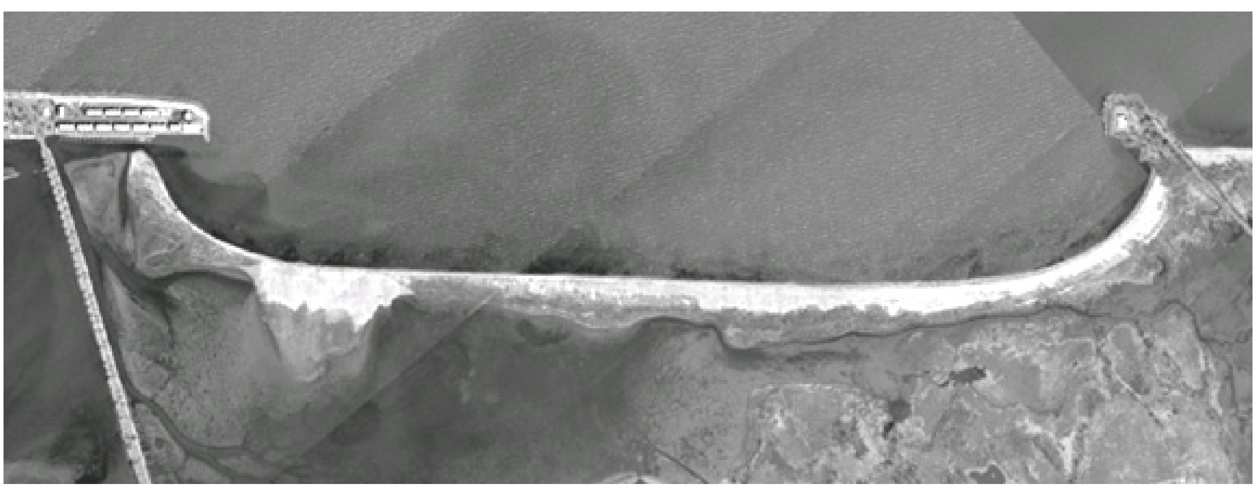

Figure 6. 2001 aerial photograph illustrating current barrier island position

Figure 7 shows a contemporary oblique aerial view of the western portion of the barrier and marsh. The condominiums on the Cedar Point spit, in the right side of the photograph, are armored with rock.

Figure 7. Oblique aerial photograph of Sheldon Marsh (western end, 1999)

PROTOTYPE CONCEPT DESIGN: When the conceptual project design phase began, the local sponsor (Ohio Department of Natural Resources) imposed several design constraints and objectives:

a. Slow the retreat of the barrier and protect the interior wetlands.

b. The project should have minimal visual impact on the natural surroundings.

c. The water portion of the proposed project should be constructed of natural materials.

d. Incoming storm wave energy should be decreased significantly.

e. Some wave energy should be allowed to reach and run up the barrier beach.

f. Some minor overtopping should be allowed.

g. Littoral sediment loss to the existing western condominium channel should be minimized.

h. Project construction should be relatively simple.

i. Maintenance should be minimal.

j. Potential fish habitat should be increased within the project area.

Fourteen alternatives were considered to satisfy the sponsor's requirements. (U.S. Army Engineer District, Buffalo, in preparation). This CHETN describes a submerged rubble-mound matrix, an innovative design that provided the best combination of engineering and environmental benefits for this site. This nonobtrusive technology will stabilize the shoreline and enhance the preserve's natural setting, biological habitats, and ecological diversity. The wide-crested and submerged segmented breakwater matrix was designed with 12.2- to 14.6-m- (40- to 48-ft-) wide by 20.7- to 21.9-m- (68- to 72-ft-) long segments consisting of dimensioned rubble-mound stones interspersed with Reefballs™ (hollow concrete hemispheres specifically developed for marine habitat enhancement. Additional information on Reefballs™ is available through the ReefBall Foundation at *www.ReefBall.org*).

Originally, cut sandstone 0.9 m (3 ft) high by 1.2 m (4 ft) wide by 1.8 m (6 ft) long were considered for the structure. However, sandstone proved to be too expensive for this application. Dimensioned rubble-mound stone is a lower cost substitute for the cut sandstone. The armor stone would have a size range of 0.9 to 1.1 m (3.0 to 3.5 ft) high by 1.1 to 1.5 m (3.5 to 5.0 ft) wide by 1.2 to 1.8 m (4 to 6 ft) long. Because only a single layer of armor stone will be placed, it is important that the side facing the bedding stone be reasonably flat to allow good contact.

PHYSICAL MODEL TESTING: The ERDC model facility consisted of a wave basin, computerized wave generator, model slope, wave gauges, and aluminum plates used to simulate the proposed submerged breakwaters (Figures 8 and 9).

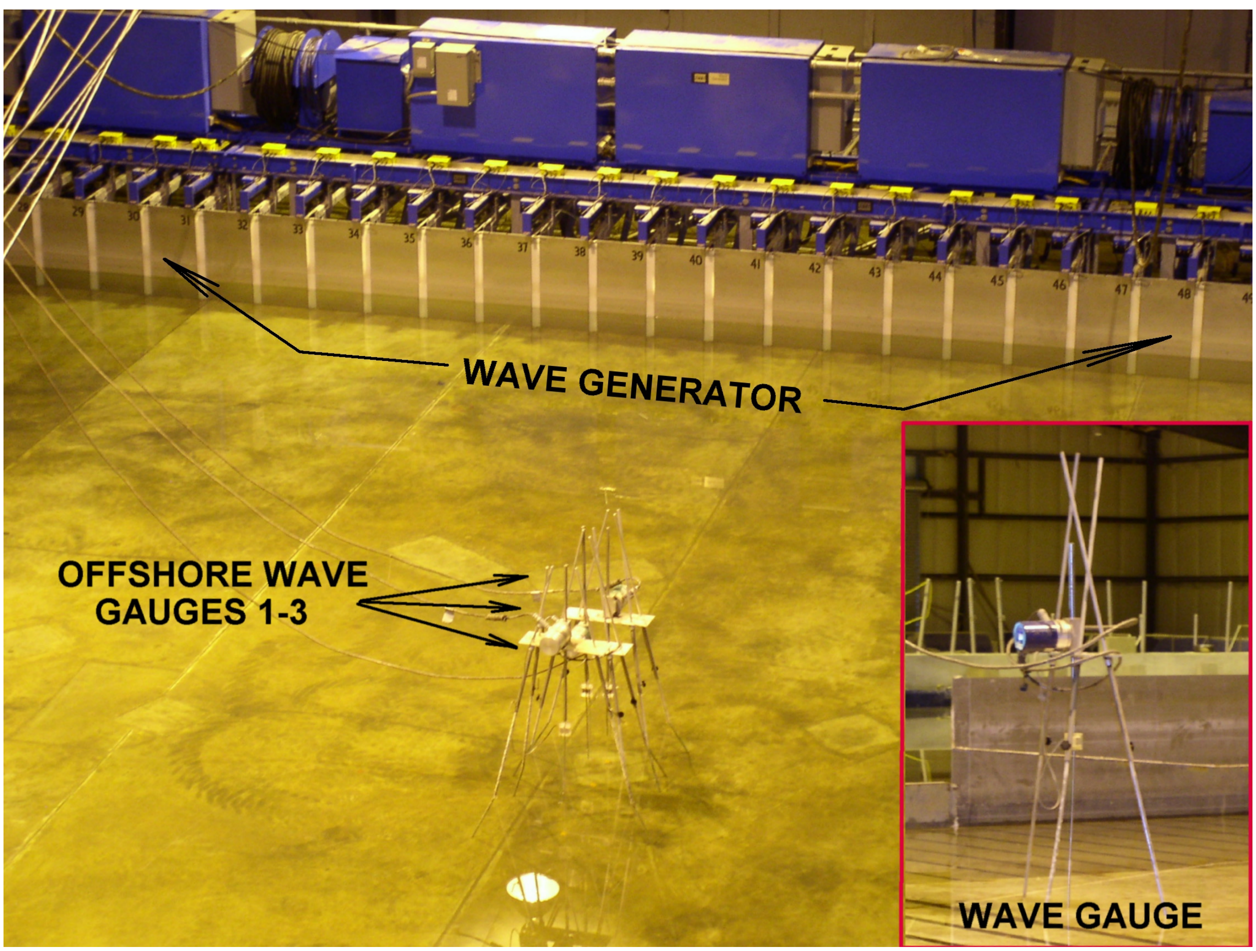

Figure 8. Photograph of wave generator and gauge configuration

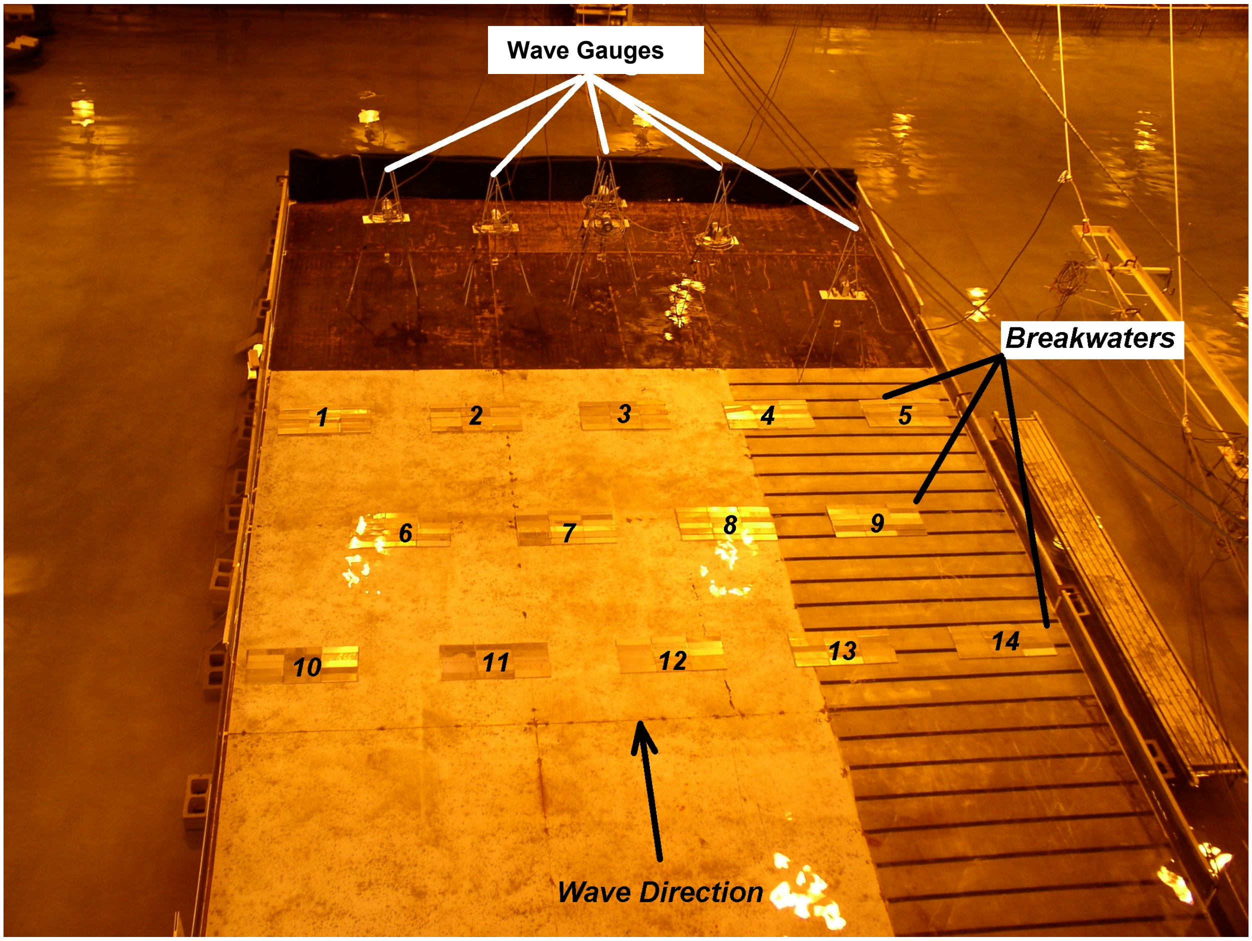

Figure 9. Photograph of initial (October 2003) model and gauge configuration

The 7.3-m- (24-ft-) wide by 25.6-m- (84-ft-) long model resides within the 61-m- (200-ft-) long by 150-ft-wide (nominal) by 1.2-m (4-ft-) deep basin. The open offshore end faces the wave generator, with aluminum vertical guide vanes placed on both sides of the model to retain the waves. The back 4.9 m (16 ft) of the basin was covered with an extruded-metal wave absorber. Rolls of rubberized matting were also placed along the sides of the basin to improve wave damping. Wave gauges were capacitance-type gauges with Jordan controllers for calibrating. All gauges used in the model study were fabricated at ERDC.

The wave generator used in the tests was a 61-paddle directional spectral wave generator (DSWG) built by MTS, Inc. The individual paddles are linked, but function independently. MTS, Inc. provided the software for running the machine via a standard personal computer (PC). Data analysis used the Generalized Experiment Control and Data Acquisition Package (GEDAP) wave analysis package developed by the Canadian Hydraulics Center. Wave signals were computed and generated using the Texel, MARSEN, and ARSLOE (TMA) (Bouws et al. 1985) spectrum for shallow-water spectral waves. All waves were run normally incident to the model.

The physical model study involved three separate sets of test runs using wave data generated at the old roadbed from the STWAVE program (Smith 2001; USAED, Buffalo, 2005). Tables 1 and 2 present lake level and offshore wave information for use in the STWAVE runs. The first run, conducted in September 2003, used an existing model slope (1:250) instead of the actual offshore slope at Sheldon Marsh (1:150). This was done to maximize initial proof of concept testing time and to optimize test procedures for the Sheldon Marsh conceptual model slope.

Table 1
Lake Level and Offshore Wave Information for STWAVE Runs

Case	Water Level			Offshore Wave				
	RI - Years	Elevation - LWD ft	Elevation - LWD m	RI - Years	Wave Height - H_o ft	Wave Height - H_o m	Period sec	Direction
1	10	6.5	1.98	20	11.5	3.5	7.7	N40°E
2	10	6.5	1.98	2	10.2	3.1	7.3	N40°E
3	10	6.5	1.98	AVERAGE	3.3	1.0	4.7	N40°E
4	AVERAGE	2.0	0.61	20	11.5	3.5	7.7	N40°E
5	AVERAGE	2.0	0.61	2	10.2	3.1	7.3	N40°E
6	AVERAGE	2.0	0.61	AVERAGE	3.3	1.0	4.7	N40°E
7	LOW	-0.6	-0.18	20	11.5	3.5	7.7	N40°E
8	LOW	-0.6	-0.18	2	10.2	3.1	7.3	N40°E
9	LOW	-0.6	-0.18	AVERAGE	3.3	1.0	4.7	N40°E

Table 2
Wave Information from STWAVE Runs at Old Roadbed

Case	Water Level			Waves at Old Roadbed				
	RI - Years	Elevation - LWD ft	Elevation - LWD m	RI - Years	Wave Height - H_o ft	Wave Height - H_o m	Period sec	Direction
1	10	6.5	1.98	20	6.8	2.07	7.7	N40°E
2	10	6.5	1.98	2	6.8	2.07	7.3	N40°E
3	10	6.5	1.98	AVERAGE	2.8	0.823	4.7	N40°E
4	AVERAGE	2.0	0.61	20	4.5	1.37	7.7	N40°E
5	AVERAGE	2.0	0.61	2	4.4	1.34	7.3	N40°E
6	AVERAGE	2.0	0.61	AVERAGE	2.8	0.823	4.7	N40°E

Note: Data were collected for only the average and 10-year water-level conditions due to gauge limitations.

The second set of model tests, using the actual Sheldon Marsh offshore slope, was completed in October 2003. Results from the first tests were used and refined during the second set of runs to determine an optimum breakwater configuration.

The third series of tests was completed in June 2004. This set implemented conceptual design improvements resulting from the October 2003 tests. The improvements included raising the submerged structure elevation to el +1 ft LWD for the shoreward breakwaters, el 0.0 for the middle row of breakwaters, and el -1 for the lakeward breakwaters and decreasing the breakwater gap slightly to take advantage of energy dissipation due to refraction and diffraction. The June tests also included several model runs of a double-row and single-row design.

Model Configurations. The concept of the segmented, multirow, submerged, breakwaters is relatively new and was expressly modeled for the Sheldon Marsh Section 227 Demonstration Project study (Figures 9 and 10). The 1:24 physical model was 7.3 m (24 ft) wide, with the 0.6- by 0.9-m- (2- by 3-ft) breakwaters spaced 0.6 m (2 ft) apart in rows 1.2 m (4 ft) apart. The breakwater crests were originally placed at el +1, el -1, and el -2, with the lowest forming the most lakeward row. Nine wave gauges were used during the October tests (10 gauges for the June 2004 tests) to measure wave heights: three lakeward of the structures (No. 1-3), and the remaining shoreward of the breakwaters (No. 4-9). During testing, waves were measured offshore and nearshore for existing (no structure) and with structure conditions for low, average, and high water level conditions (USAED, Detroit, 1993), and for average, 2-year and 20-year wave heights (Driver et. al. 1991; Resio and Vincent 1976). Tables 3 and 4 summarize the measured data. Data were not collected for the low water level condition, as there was insufficient water depth to operate the nearshore gauges.

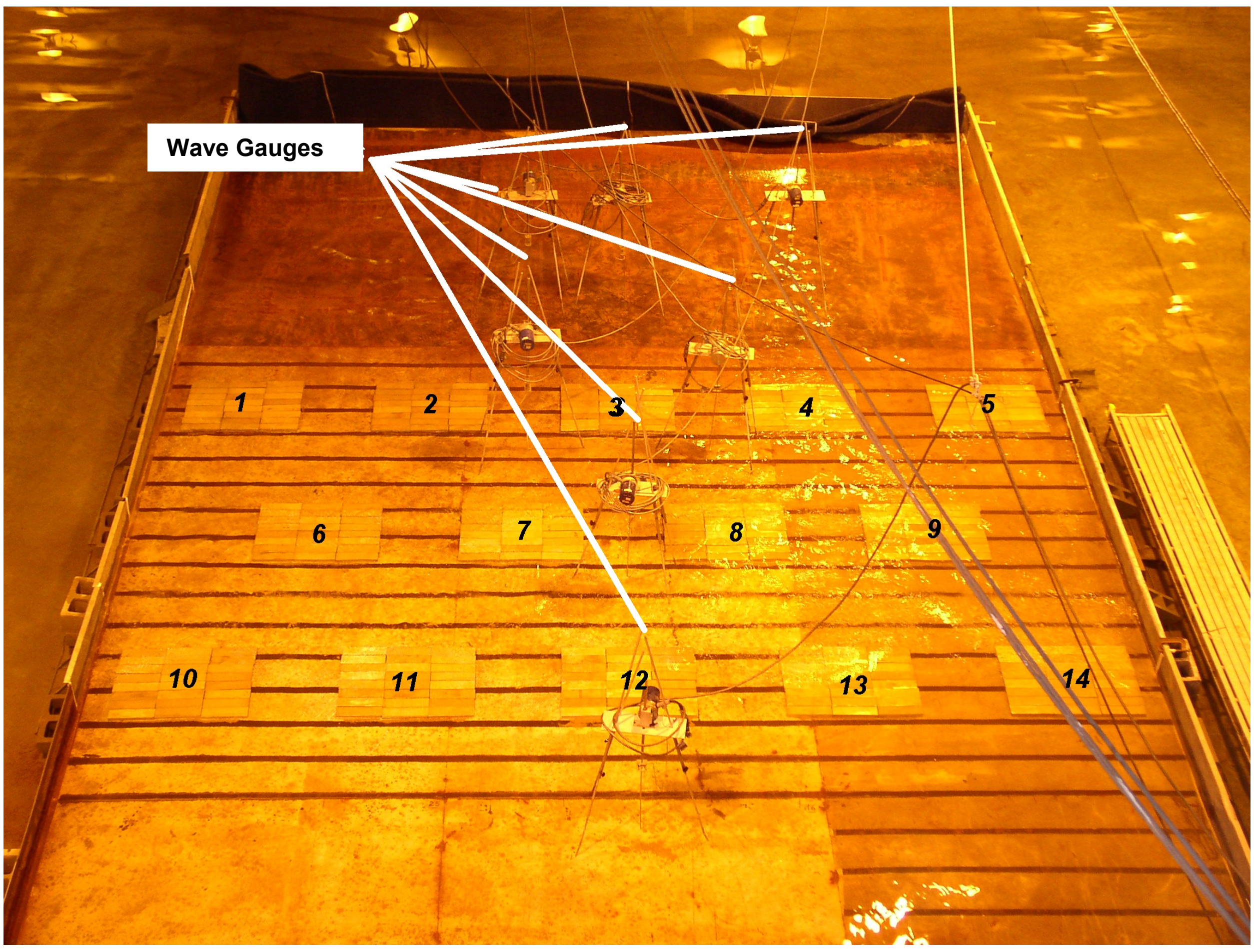

Figure 10. Photograph of final model and gauge configuration (June 2004)

Table 3
Summary June 2004 Model Tests – Average Water Level

Waves	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10
Average of Baseline Tests for Average Water Level (real-world measurement - ft)										
20-year Wave Height	4.522	4.444	4.429	3.235	3.319	2.926	3.202	3.055	2.258	2.197
2-year Wave Height	4.431	4.364	4.391	3.299	3.226	2.892	3.150	2.722	2.245	2.124
Average Wave Height	2.806	2.787	2.806	2.180	2.342	2.351	2.272	2.490	1.949	1.917
Tests for Average Water Level (real-world measurement - ft)										
20-year Wave Height	4.488	4.423	4.376	3.165	2.743	2.046	2.145	1.685	1.494	1.361
2-year Wave Height	4.405	4.360	4.380	3.102	2.734	2.162	2.199	1.754	1.532	1.414
Average Wave Height	2.837	2.806	2.820	2.276	2.361	1.710	1.885	1.281	1.163	1.085
Average Water Level - Percent Wave Height Remaining										
20-year Wave Height				97.834	82.657	69.914	66.995	55.155	66.179	61.935
2-year Wave Height				94.021	84.745	74.772	69.816	64.458	68.257	66.580
Average Wave Height				104.408	100.790	72.752	82.967	51.455	59.677	56.615
Note: 5 by 4 by 5 rows, 2-ft-wide gap and 3.5-ft cross-shore gap, 3-ft-long by 2-ft-wide breakwater.										

Table 4
Summary June 2004 Model Tests – 10-year Water Level

Waves	Average of Baseline Tests for 10-year Water Level (real-world measurement - ft)									
	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10
20-year Wave Height	7.039	6.977	6.940	5.300	5.386	4.663	5.647	4.467	4.926	4.520
2-year Wave Height	6.985	6.935	6.927	5.137	5.427	4.778	5.419	4.350	4.617	4.484
Average Wave Height	2.737	2.730	2.717	1.990	2.066	2.143	1.966	2.073	2.076	1.985
Tests for 10-year Water Level (real-world measurement - ft)										
20-year Wave Height	7.042	6.967	6.899	5.554	4.979	4.420	4.908	3.842	3.950	3.791
2-year Wave Height	7.089	7.035	7.004	5.470	5.057	4.634	4.819	3.915	3.943	3.896
Average Wave Height	2.659	2.649	2.592	2.031	2.421	2.927	2.762	1.551	2.858	2.720
10-year Water Level - Percent Wave Height Remaining										
20-year Wave Height				104.776	92.442	94.791	86.907	86.011	80.173	83.870
2-year Wave Height				106.476	93.188	96.976	88.928	89.991	85.417	86.883
Average Wave Height				102.038	117.188	136.579	140.489	74.820	137.709	137.009
Note: Data values collected for the 10-year design water level and average wave height indicate higher values due to the actual gauge location and wave steepening. Wave energy will be dissipated, since the gauges were placed in a position before the waves began to break, the additional wave reduction was not recorded.										

Wave Data Results. The final tests were of an optimal armor unit configuration that was based on refinements of earlier tests. Figure 11 illustrates the chosen model configuration with real-world dimensions.

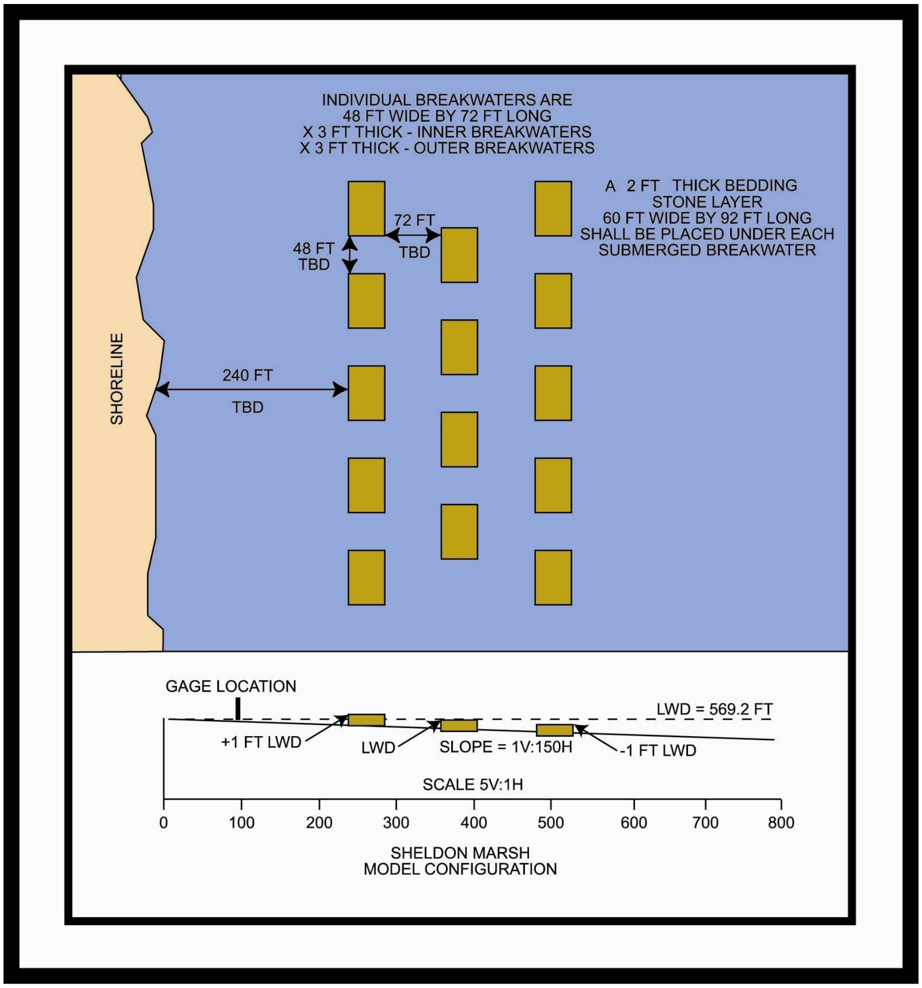

Figure 11. Model configuration with real-world dimensions

The data illustrate that at an average water level, a wave height reduction in the range of 34 to 46 percent is expected. At the 10-year design water level, a wave height reduction in the range of 13 to 23 percent should occur. The physical model results are based on a model constructed with a relatively smooth slope made of aluminum plates. Also, the wave gauges were located approximately 45.7 to 60.9 m (150 to 200 ft) (real-world scale) from the shoreline due to the need for a minimum water depth to achieve accurate wave information. Additional wave attenuation is anticipated to occur due to the rubble-mound structures' roughness and additional wave breaking as the waves approach the shoreline. This additional wave reduction is conservatively expected to be in the range of 5 to 10 percent.

Figures 12-14 present the measured wave attenuation for the existing conditions and for expected conditions with the proposed project. The figures indicate an increase in water level between the offshore Gauges 1-3 and Gauge 4 just lakeward of the breakwaters. This is misleading because of a lack of intermediate data points. In reality, there is only a local increase in water level at Gauge 4 due to the influence of the breakwater. Table 5 summarizes the average wave reduction at the nearshore.

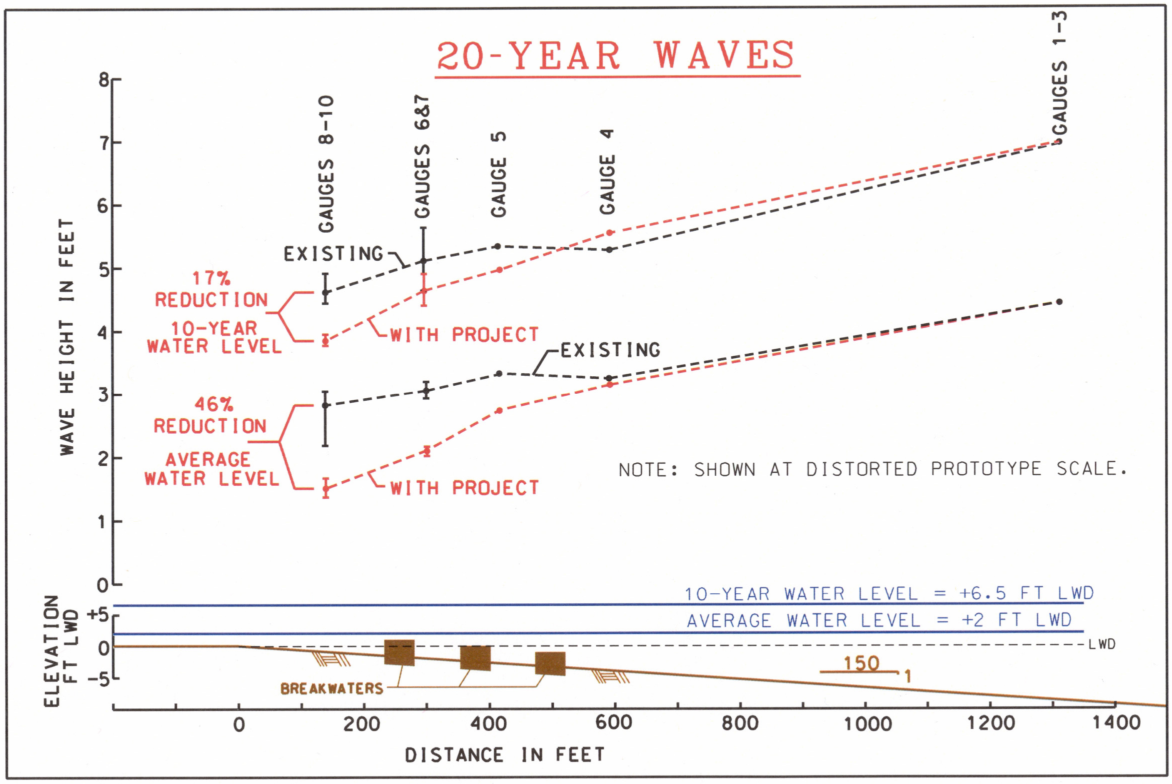

Figure 12. 20-year wave summary graph

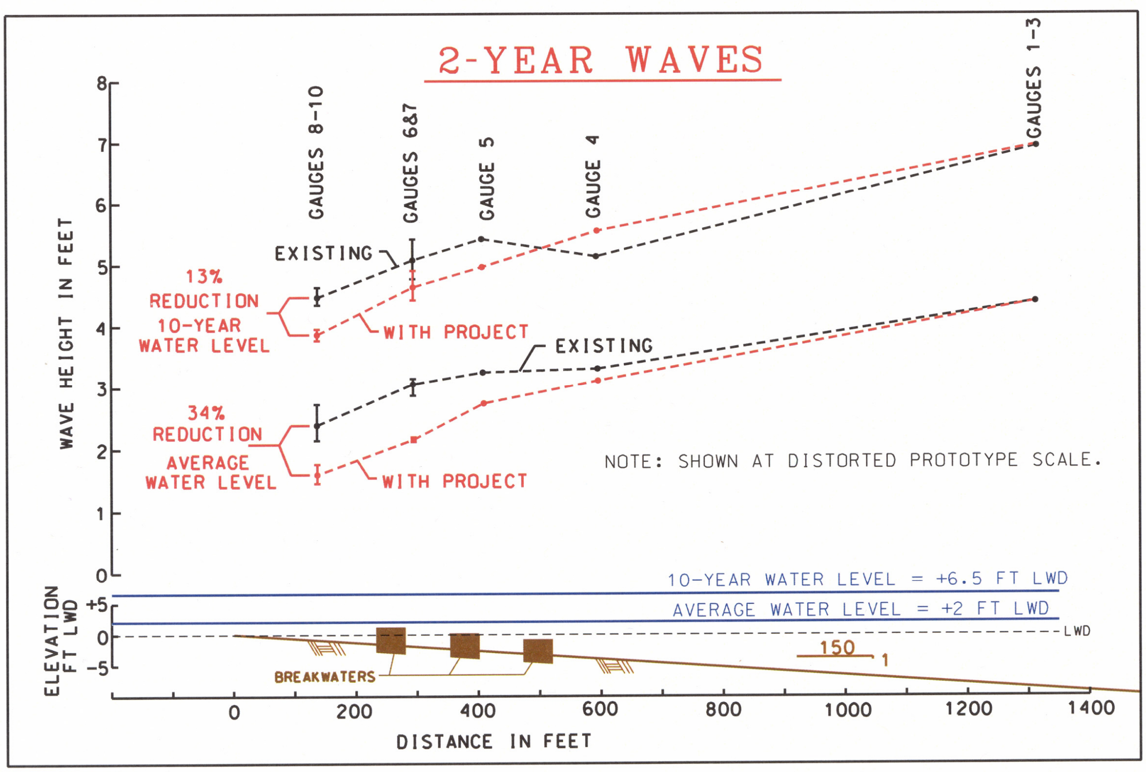

Figure 13. 2-year wave summary graph

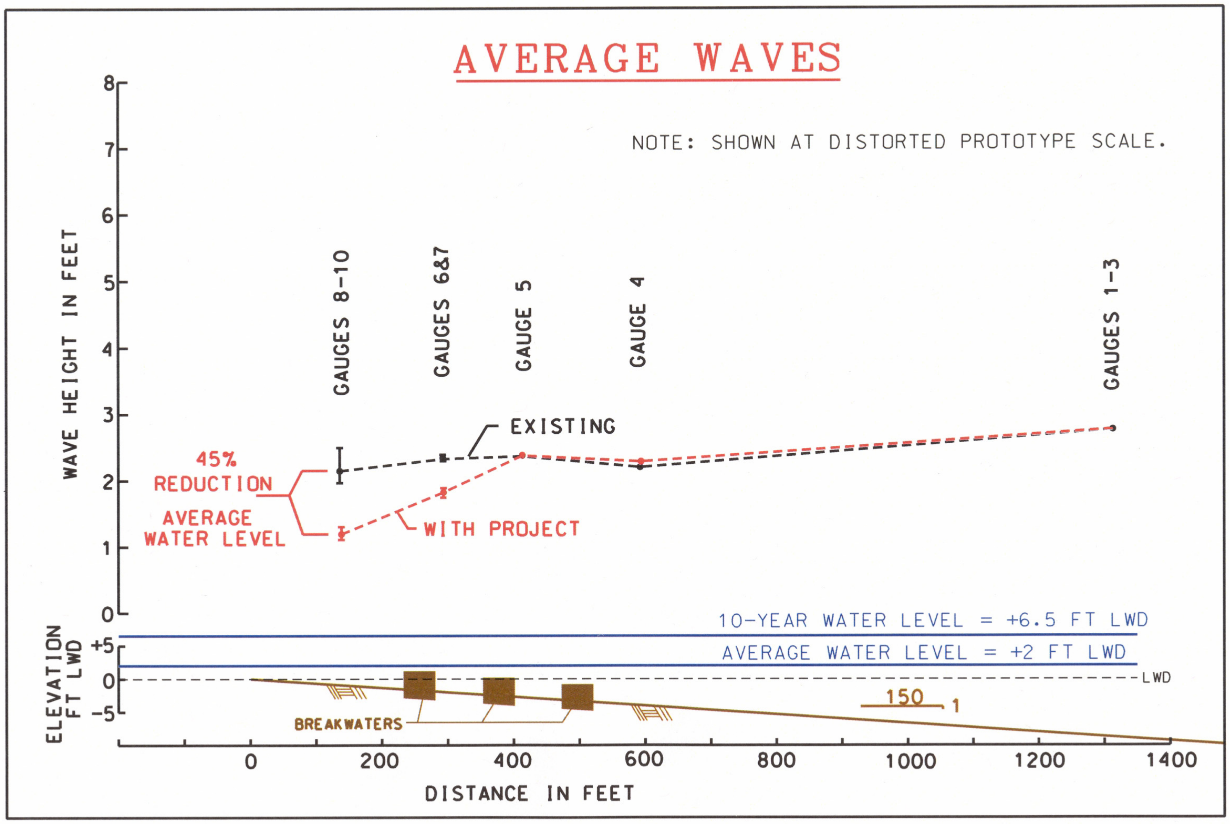

Figure 14. Average wave summary graph

Table 5
Summary June 2004 Model Tests

Water Level	Wave Recurrence Interval	Average Wave Height		Percent Reduction
		Existing	With Project	
Sheldon Marsh Physical Study Model - Average Wave Height at Gauges 8-10				
Average	Average	2.119	1.176	45
	2-year	2.364	1.567	34
	20-year	2.803	1.513	46
10-year	Average	3.067	2.376	23
	2-year	4.484	3.918	13
	20-year	4.638	3.861	17

SUMMARY: The Section 227 Program provides a unique opportunity in the United States to implement a full-scale prototype project and verify its effectiveness in a coastal setting. The premise of the Section 227 Program is to test various innovative or nontraditional methods of coastal shoreline erosion abatement.

A submerged, segmented breakwater system is proposed at Sheldon Marsh, OH. The submerged breakwater system would be relatively unobtrusive, would decrease wave energy, and provide protection for the fragile coastal barrier. Water circulation would be maintained through the gaps and additional fish habitat would be provided by the stone bedding material and Reefballs™ interspersed throughout each breakwater. Physical model testing indicated a nearshore wave reduction between 13 and 23 percent during a 10-year water level and 34 to 46 percent reduction during average water levels.

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