ONELINE, A NUMERICAL MODEL FOR SHORELINE CHANGE

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Abstract

This paper describes the latest revision of the Queen's University coastal morphology model ONELINE. The model provides practical and reliable full, time-dependent simulations of shoreline change for coasts controlled by structures and complex boundary conditions. ONELINE calculates shoreline change due to longshore sediment differentials as well as on-offshore sediment movements. Model tests and case studies from around the world were conducted to test ONELINE's capabilities. Two case studies for Sea Isle City beach, New Jersey, and along the Nile Delta Coast in Egypt are discussed in this paper. Results are compared with observed field measurements to examine the model capabilities.

Introduction

The increasing development of coastal areas is faced with persisting erosion and flooding problems. Almost two-thirds of the world's population reside within 200 km of the coast, and continuous engineering activities are needed to safeguard coastal areas from erosion and flooding. Comprehensive coastal zone management and erosion/flood control requires a reliable and practical tool for predicting shoreline evolution to optimize shore protection measures.

One-dimensional coastal morphology models (one-line models) have demonstrated practical capability in predicting long-term shoreline change. However, most one-line models suffer from various constraints that limit their wide applicability. Work is currently in progress at Queen's University on upgrading ONELINE, a shoreline morphology model developed earlier, to create a practical shoreline change model with wide applicability for complex beach system configurations. The main objective is to provide accurate predictions that match the quality of available input data and knowledge of sediment transport processes

ONELINE is based on the one-line theory of shoreline change, but does not make any small angle assumption with respect to the incident wave angle and the shoreline

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direction. The work on ONELINE was started in 1988 and was followed by several refinements to improve the model's capabilities. The latest upgrades include the cross-shore sediment transport contribution to shoreline change, the capability to simulate shoreline response to any combination of off-shore or shore-connected structures, improved formulation of the lateral boundary conditions, and provision of a Windows-based user interface that renders a user-friendly environment.

This paper provides a brief description of the ONELINE modeling system and demonstrates its capabilities through model tests and case studies. Two case studies are described in which complex beach system configurations are simulated. The first one features a groin field at Sea Isle City, New Jersey along the East Coast of the United States. The second is along the Nile Delta Coast in Egypt and includes detached breakwaters, groins, seawall, and a river mouth boundary. Simulation results are compared with measured shorelines to examine the model's capability of predicting shoreline change.

Model Description

Following the one-line assumption that the beach profile moves parallel to itself out to a limiting depth of closure (d_C), conservation of sediment for an infinitely small length of shoreline, Δx, can be expressed as follows (Figure 1):

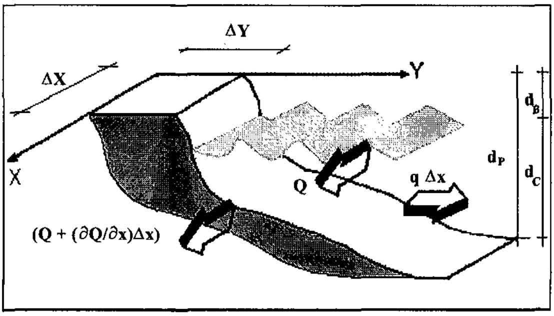

Figure 1. Definition sketch of conservation of sediment

$$\frac{\partial y}{\partial t} = -\frac{1}{d_p}\left(\frac{\partial Q}{\partial x} + q\right) \tag{1}$$

where y is the shoreline position, x is the longshore coordinate, t is the time, Q is the longshore sediment transport, q represents the average on-offshore transport rate, and d_P is the profile depth which equals the closure depth d_C plus the beach berm height d_B. The present model uses the Kamphuis formula (Kamphuis, 1991) modified to include transport by wave height gradient (Hanson and Kraus, 1989) to calculate longshore sediment transport (Equation 2).

$$Q = CKH_b^2T^{1.5}\beta^{0.75}D^{-0.25}\left[\sin^{0.6}(2\alpha_b) - \frac{2}{\beta}\cos\alpha_b\frac{\partial H_b}{\partial x}\right] \tag{2}$$

where Q is the alongshore sediment transport rate, C is a constant that is 7.3 when Q is expressed in m^3/hr., K is the ratio of actual over potential sediment transport rate (used as an empirical factor for model calibration), H_b is the breaking wave height, T is the wave period, β is the beach slope in the breaking zone, α_b is the breaking wave angle, and D is the nominal grain size. Cross-shore sediment transport is calculated using Bailard's 1982 model (Equation 3).

$$q = k_s \frac{\rho C_f u_b^3}{(\rho_s - \rho) g p} \left\{ \frac{\varepsilon_B}{\tan\phi} \left(\psi_1 + \frac{2}{3}\delta_u - \frac{\tan\beta}{\tan\phi} u_3^* \right) + \frac{u_b}{\omega_s} \varepsilon_S \left[\psi_2 + \delta_u u_3^* - \frac{u_o}{\omega_s} \varepsilon_S \tan\beta u_5^* \right] \right\} \quad \text{.....(3)}$$

In which δ_u, ψ_1, ψ_2, u^*_3, and u^*_5 are cross-shore velocity moments defined by Bailard (1982) as functions of wave height; ϕ is the angle of internal friction; ε_B and ε_S are the coefficients of bed load and suspended load efficiency; C_f is the drag coefficient, u_b is the fluid bottom velocity, ρ and ρ_s are the fluid and sediment densities respectively, p is the sediment concentration, ω_s is the fall velocity, and k_s is an empirical factor used for calibration.

The basic ONELINE model structure is illustrated in Figure 2. The modeled shoreline is discretized into a finite grid and the simulation time is divided into time steps. For each time step wave shoaling, refraction, diffraction and the resulting sediment transport are calculated at each grid point. Then, the governing equations are solved simultaneously in the form of a matrix to determine the new shoreline.

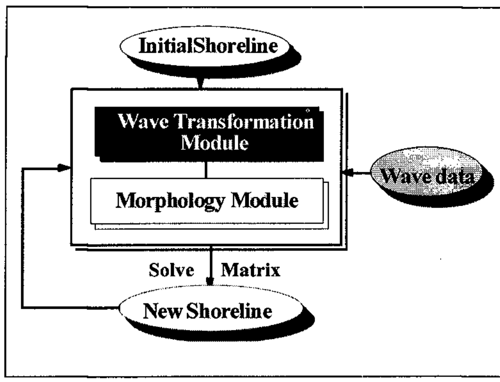

Figure 2. ONELINE model structure

The updated version of ONELINE includes improved mathematical formulation of boundary conditions and internal constraints. The new lateral boundary conditions give the modeler greater control in defining complex conditions near the boundaries. User-specified inflow and outflow factors at each boundary are used to define the sediment transport gradients at the boundaries. Boundary conditions can be properly formulated through sensitivity analysis and model calibration with observed shorelines. These highly adaptable boundary conditions provide the capability to simulate a wide range of complex beach system configurations with various sources or sinks near the boundaries. For example, sources such as river sediment discharges, updrift feeder beaches where nourishment occurs outside the modeled area, and sinks such as tidal inlets, or submarines canyons can all be modeled. Likewise, the representation of internal constraints such as groins or breakwaters was significantly improved to provide accurate response of shoreline to nearshore structures. The mathematical formulation of the influence of various structures on wave transformation and morphological changes was refined, tested, and calibrated with various model runs and case studies from around the world.

Model Tests

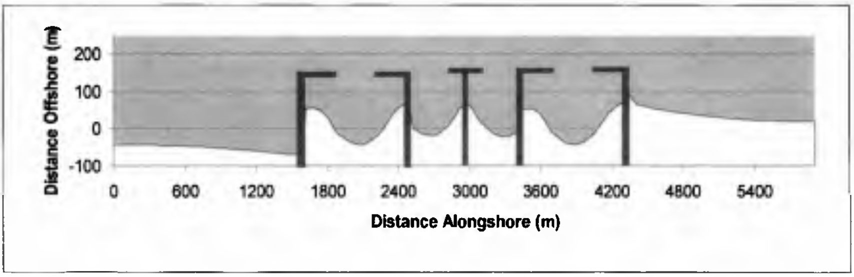

Figure 3a. Shoreline response to coastal structures

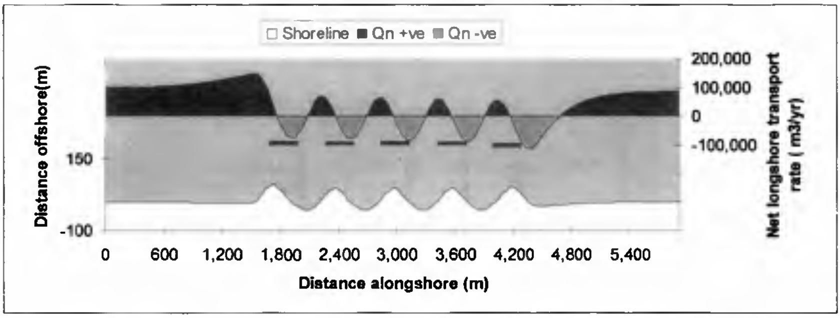

Figure 3b. Shoreline response and longshore transport patterns near breakwaters

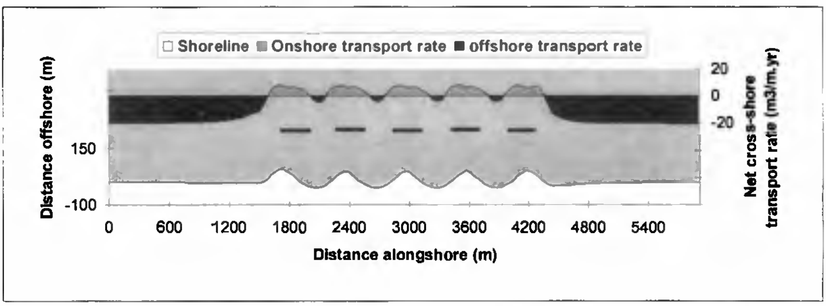

Figure 3c. Shoreline response and cross-shore transport pattern near breakwaters

Figure 3. Model test results

Several model tests were performed to examine ONELINE's new formulations. Figure 3a shows the result of a 5-year simulation on a straight beach with various coastal structures subjected to an annual wave time series with 4-hour time step. Figure 3b shows simulation results of the net longshore transport rate distribution near a series of detached breakwaters subjected to measured wave time series. Figure 3c indicates simulated cross-shore transport patterns near breakwaters subjected to big waves. The breakwaters reduce wave heights behind them yielding on-shore sediment movement unlike the open coast areas where larger waves produce net offshore sediment losses. The results reflect ONELINE's realistic simulation of the influence of coastal structures on wave transformation, sediment transport and shoreline change.

Two cases are discussed in this paper to demonstrate the capability of ONELINE The cases were selected along Sea Isle City beach, New Jersey, USA, and the Nile delta coastline in Egypt.

Sea Isle City Model

The first case study is a 15-year simulation of a groin field at Sea Isle City, New Jersey. Sea Isle City faces the Atlantic and is located at the south end of Ludlam Island, a barrier island in southern New Jersey, USA (Figure 4).

Background

Sea Isle City coastline is a fine sandy beach backed by sand dunes. The predominant waves come from northeast direction producing an average net longshore transport of about 300,000 m^3/yr to the south (Everts 1979). To stabilize the beach and reduce erosion rates along Ludlam Island, several groins have been constructed to form a groin field. Early groins were built at the northern part of the Ludlam Island by the turn of this century. The groins were low in profile and relatively short so that they would not produce large shoreline offset across them. The groin system along with periodic nourishment maintained a wider, more stable beach within the groin compartments. However, erosion was shifted to the beach downdrift of the southermost groin. Thus, over the years, the groin field was extended southward to cover most of the island shoreline.

Figure 4. Sea Isle City location

Model Setup

The Sea Isle City model covers 2.6 km between a groin field at the northern boundary and a tidal inlet at the southern boundary (Figure 5). ONELINE modeled this shoreline reach by 75 grid cells 35 m long each. The input wave data were determined from measured wave gauges near Sea Isle City. The simulations were carried out in two phases for the period between November 1980 and March 1995 with a 4-hour time step, generating a total of 11,406 time steps. The first simulation phase from 1980 to 1986 was used for model calibration. During that simulation period 4 groins were added in 1983. Calibration involved the determination of the sediment transport calibration constants, and appropriate representation of the lateral boundary conditions and internal constraints. The fast execution time of ONELINE simulations allowed sensitivity analyses for each of those controlling parameters. Thus, several runs were performed: first to estimate the sediment transport factors to give average transport rates close to the estimated or measured rates; then the lateral boundaries were adjusted so that the observed sediment losses or gains for the area were correct, and finally, the internal

Figure 5. Sea Isle City model setup

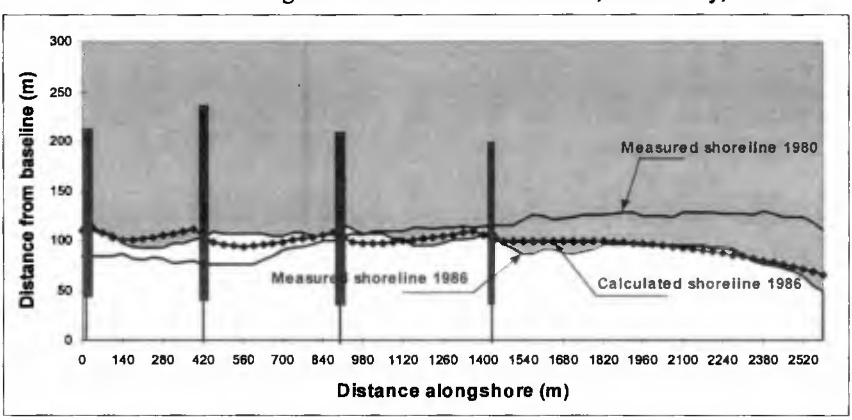

Figure 6. Model calibration results

constraints (structures on the grid) were adjusted by changing groin permeability to provide good agreement between predicted and measured shorelines near the structures.

Figure 6 shows the calibration results. The averaged prediction error (E_P) for the calibration phase was 10%, where E_P is the average of all the absolute values of the error of calculated shoreline change at each grid point. Following calibration, the second simulation phase from January 1986 to March 1995 verified the calibrated model. During that period two more groins and two major beach fills were added and still verification showed close agreement of measured and predicted shorelines of 1995 with E_P = 9% (Figure 7).

The Simulations of Sea Isle City beach showed the effectiveness of ONELINE's improved features. Of particular concern was the simulation of the southern boundary formed by the tidal inlet. The beach morphology close to that inlet is greatly affected by the inlet processes and realistic simulation of the sand influx across the boundary was crucial to the reliability of the predictions. The adaptable formulation of the lateral boundary conditions in ONELINE enabled a reasonable presentation of that complex boundary condition. The improved formulation of internal groins also provided accurate shoreline response within the groin field of Sea Isle city over a 15 year simulation period as shown in Figure 7. The top part of Figure 7 shows the net shoreline change along the modeled area where 6 groins and half a million cubic meters of sand were added over a period of 15 years. ONELINE succeeded in identifying locations and magnitudes of erosion and accretion along the modeled region.

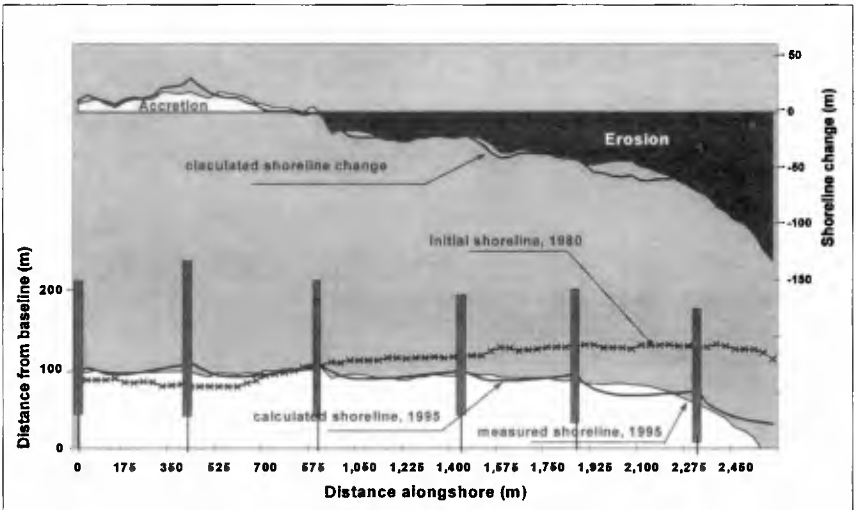

Figure 7. Sea Isle City model verification and final results

Ras-El-Bar Model

The second case study is of a rather complex beach system along the Nile Delta Coast in Egypt. The Nile Delta was formed by the Nile river sediment discharges into the Mediterranean Sea over thousands of year. Human intervention with the natural system of the Nile has profoundly modified the geological processes in the northern delta. Since completion of the Aswan High Dam in 1964, fluvial sediments are no longer transported to the coast, and the balance between fluvial and marine processes has been completely modified. The Nile Delta is not an active delta anymore, but an entirely wave-dominated coastal plain. Widespread erosion along the Nile delta coastline became a persisting problem and large-scale coastal projects have been implemented to combat coastal erosion. Ras-El-Bar is a site along the Nile delta west of the Damietta Nile branch (Figure 8). The Nile Delta coastline runs generally west to east, while local orientation of Ras-El-Bar shore is southwest to northeast. Thus only waves coming from west to northeast can reach the nearshore zone of Ras-El-Bar. The predominant wind directions offshore of Ras-El-Bar are from NW and WNW (Delft,1987). Wave records from 1985 to 1990 near Ras-El-bar indicate that the maximum and average offshore wave heights were 4.5m and 0.6 m respectively (Coastal Research Institute Alexandria, 1996).

Figure 8. Ras-El-Bar location

Ras-El-Bar beach is composed of very fine sand with average median diameter of about 0.12 millimeters. Several studies along the Egyptian coast provide sufficient description of sediment transport at Ras-El-Bar (Inman and Jenkins, 1984; Frihy and Komar, 1991). The general net longshore transport is eastward, but due to local shoreline orientation near the Damietta mouth, the local net transport is to the west. Although Ras-El-Bar represents a littoral-drift convergence zone, the accretion is small and secondary to offshore losses caused by cross-shore transport. Longshore transport at Ras El Bar is small in both directions and the net transport is minimal. Cross-shore transport plays a significant role in the shoreline change at Ras-El-Bar. Shoreline recession due to cross-shore transport was estimated in Delft Hydraulics (1987) to be about 3 to 5 m/year.

Several erosion control measures have been taken to stabilize the beaches of Ras-El-Bar (Figure 9) after the construction of the Aswan Dam. Three groins were constructed in 1970 in an attempt to eliminate the erosion of Ras-El-Bar peninsula. The groin system was not successful because the cross-shore sediment transport dominates. A dolos and riprap revetment was placed within the groin field to protect a nearby highway. Erosion was maximum at the western end-groin and diminished to the west. The erosion threatened Ras-El-Bar resort community, and further shore protection was needed to restore its eroding beach. A system of detached breakwaters was constructed in 1990, west of the groin field. The breakwaters were placed 400 meters offshore such that they would restore the recreational beach while being far enough offshore to prevent tombolo formation. In 1994, the beach area east of the breakwaters was nourished with two hundred thousands cubic meter of sand.

Model Setup

A complete time dependent simulation of shoreline changes over a 9-year period for Ras-El-Bar beach was carried out using ONELINE. The modeled area embodied a number of coastal protection works and rather complex boundary conditions. The modeled region covers 4 kilometers of beach west from the Damietta Nile mouth. This shoreline reach was modeled in ONELINE by 200 grid cells 20 m long each. The focal point of the model is the four detached breakwaters built in 1991. The breakwater system covers 1.4 km of beach; however the modeled region was extended far enough to include all the nearby littoral barriers affecting the hydro-sedimentological regime in the area. Figure 9 shows the model location and coordinate system and Figure 10 shows the modeled region schematically. Measured shorelines of 1986, 1993, and 1995 were digitized from the surveying and contour maps and transformed to the model coordinate system. Input wave data were generated using measured time series at Ras El Bar (Coastal Research Institute Alexandria, 1996). The wave gauge was located at the eastern side of Damietta promontory at 7-meter depth of water. The simulation runs covered the period from June 1986 to September 1995 on two phases. Phase one was from 1986 to 1993 during which

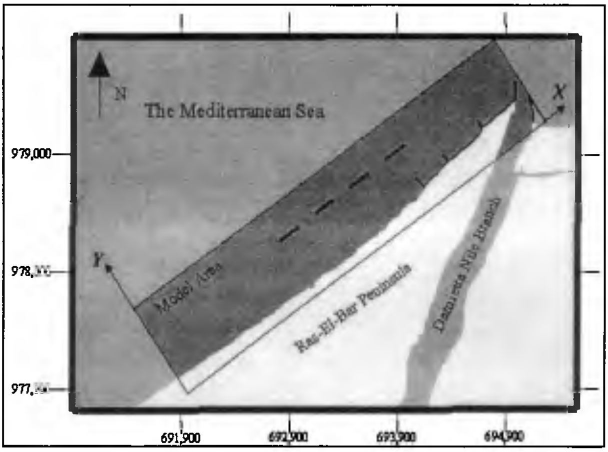

Figure 9. Model location and coordinate system

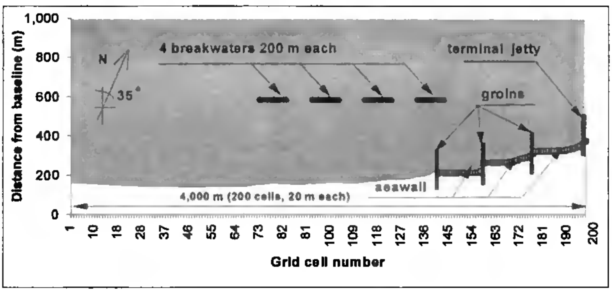

Figure 10. Schematic diagram of the modeled region

the 4 breakwaters where built in 1991, while phase two was from 1993 to 1995. A time step of 2 hours was used in all simulations, yielding a total of 40,500 time steps.

Model Calibration and Verification

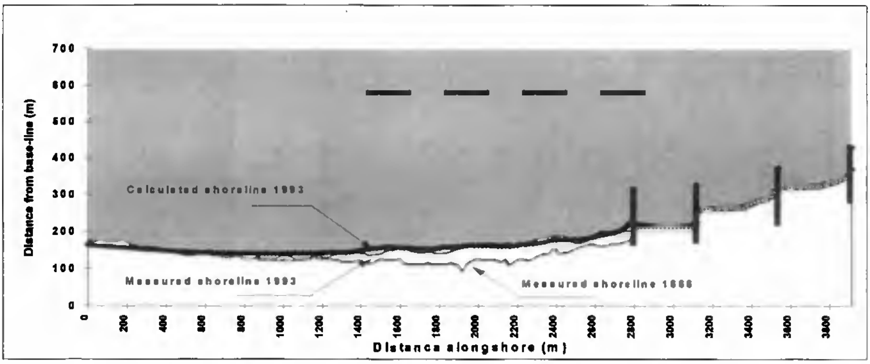

Figure 11. Ras-El-Bar model calibration results

The model was calibrated and verified with measured shorelines of 1993 and 1995 respectively. During the calibration process, first the calibration coefficient for longshore and cross-shore transports were adjusted to provide values within reasonable ranges of measurements and observations; then the lateral boundaries were set to match the inflow and outflow of sediment through both boundaries with the prototype

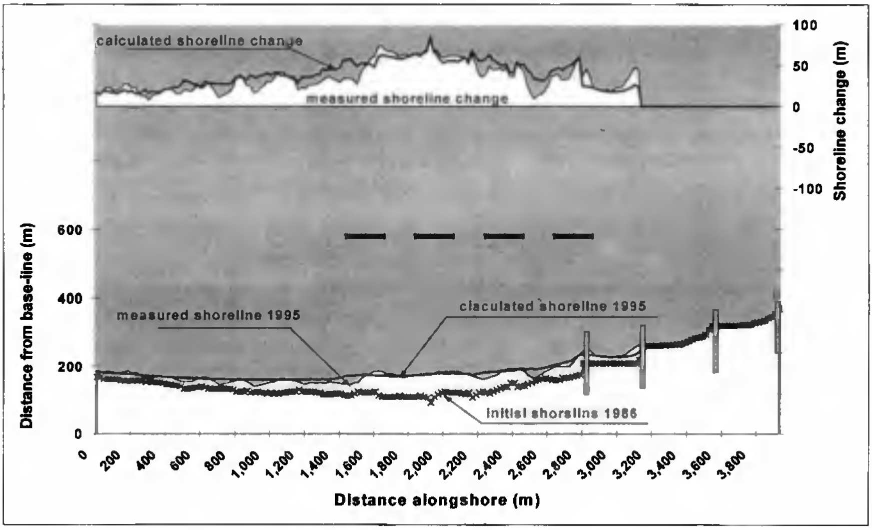

Figure 12. Ras-El-Bar model verification and final results

conditions; and finally the internal constrains such as the properties of the jetty, groins, and breakwaters were set to fine tune the calculated shoreline to match the measured shoreline.

Figure 11 shows the model calibration results. The averaged prediction error (E_p) on calibration was 13%, while for the verification was E_p =12%. Figure 12 shows the model verification and final results. A plot of the net shoreline change over the nine-year simulation period is also shown in Figure 12. ONELINE has successfully calculated the shoreline buildup behind the breakwaters due to the combined effect of longshore and cross-shore sediment transport. The results also indicate success in calculating sand bypassing and buildup seaward of the revetment in the westerly groin compartment.

Model Results

Figures 13 to 16 show samples of Ras-El-Bar model results and demonstrate the realistic simulations of coastal processes in the vicinity of various coastal structures.

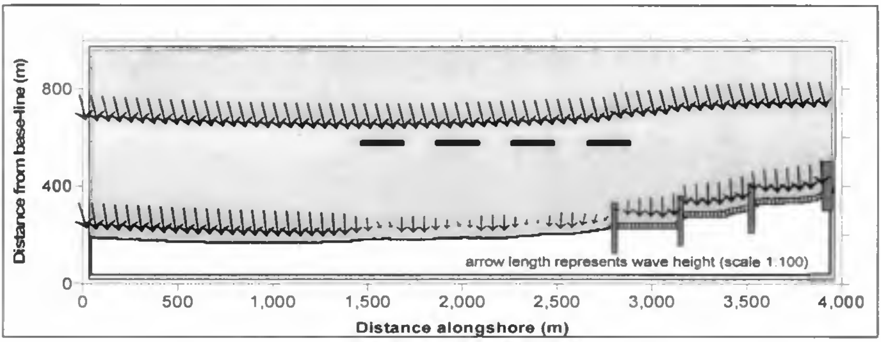

Figure 13. Wave transformation patterns

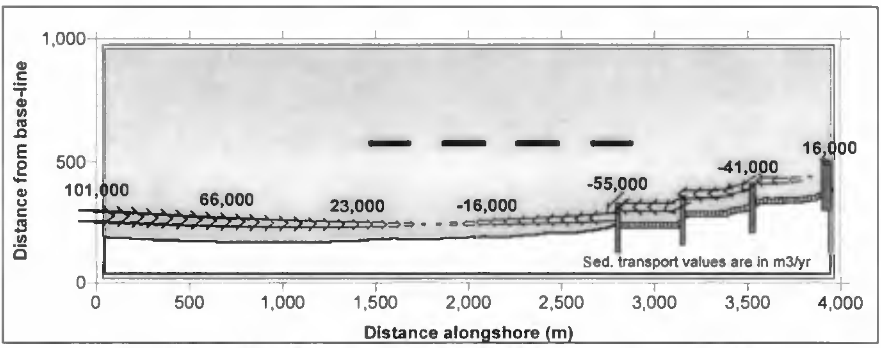

Figure 14. Net annual longshore transport rates along the modeled area

Figure 13 shows the calculated wave transformation patterns for a particular incident wave along the modeled area. ONELINE wave transformation calculations take into account the influence of wave shoaling, refraction, and diffraction for each wave event. The spatial change in wave heights and directions along the modeled region reflects clearly the diffraction patterns from different structures. The calculated longshore and cross-shore transport rates are shown in Figures 14 and 15 respectively. The model results correspond well with the field measurements and observations. The model results show how the breakwaters reduce the wave energy and consequently the sediment transport in the shadow zones. The smaller waves in the shadow zones move sediment on-shore, unlike outside the breakwater protected area where the cross-shore transport produces substantial offshore losses.

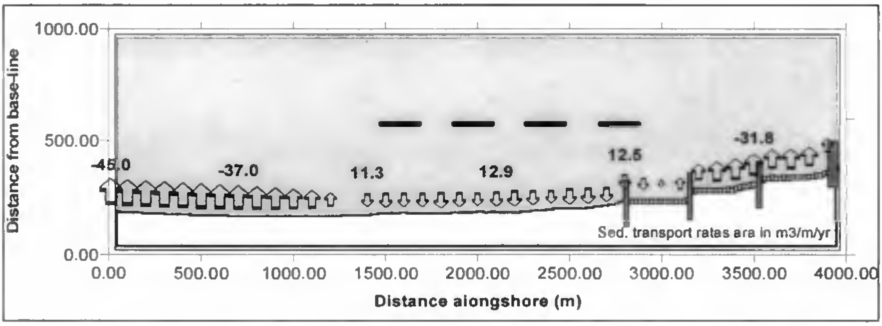

Figure 15. Net annual cross-shore sediment transport along the modeled area

Sediment Budget

Sediment budget analyses based on model results were conducted before and after the placement of the breakwaters. Figure 16 demonstrates the effects of the breakwater system on the sediment regime at Ras-El-Bar. The sediment transport rate entering the region from western boundary was around 100,000 m^3/yr. while only 16,000 m^3/yr. bypass the terminal jetty at the eastern boundary. The breakwater system reduced the offshore losses from 167,000 m^3/yr. to 42,000 m^3/yr. The sediment budget analyses indicate that before the construction of the breakwaters, a net loss of 83,000 m^3/yr (equivalent to shoreline erosion of an average 2.3m/yr) while after the construction a gain of 42,000 m^3/yr. is attained (equivalent to a shoreline gain of an average 1.4m/yr.).

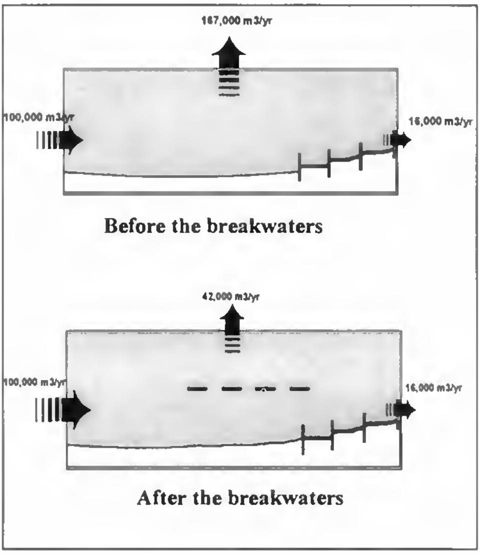

Figure 16. Sediment budget results

Conclusion

This paper describes, ONELINE, a shoreline change modeling system, and demonstrates its capabilities through model tests and case studies. ONELINE's recent improvements boosted its practical applicability to simulate more complex beach system configurations. Model tests indicated ONELINE's credible predictions of sediment transport and shoreline response to various combinations of coastal structures. Two case studies were simulated to verify the model capabilities. A 15-year simulation of a 2.6-km shoreline reach at the southern part of Sea Isle City, New Jersey, proved the effectiveness of ONELINE to simulate shoreline response to permeable groins and complex boundary conditions. The refined formulation of lateral boundary conditions enabled reasonable presentation of the tidal inlet boundary of Sea Isle City model. ONELINE was also used to model Ras-El-Bar, a beach resort area along the rapidly eroding Nile delta. Several erosion control measures were built over the years such as breakwaters, groins, seawall, and river mouth jetties. A 9-year simulation of a 4 km-long beach at Ras-El-Bar was successful. The adaptable boundary conditions of ONELINE enabled simulation of the sediment flow patterns at the jettied river mouth of the eastern boundary as well as longshore transport gradients at the western boundary. Cross-shore sediment transport plays a large role in the shoreline change at Ras-El-Bar. ONELINE's ability to simulate cross-shore sediment transport as well as longshore transport in the vicinity of different coastal structures allowed a successful modeling of these complex beach systems. The model results corresponded with the field measurements and hence provided quantitative results and a well-verified prediction capability of the region. The consistently small prediction error on calibration and verification of these widely varying cases demonstrates the robustness of ONELINE. The modeling system, ONELINE, is still under development. Future improvements include upgrading ONELINE to contour lines model to enable predictions of profile changes as well.

Acknowledgments

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