Beach-*fx*: Monte Carlo Life-Cycle Simulation Model for Estimating Shore Protection Project Evolution and Cost Benefit Analyses

By

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ABSTRACT

Beach-*fx* is a comprehensive new analytical framework for evaluating the physical performance and economic benefits and costs of shore-protection projects, particularly, beach nourishment along sandy shores. The model has been implemented as an event-based Monte Carlo life cycle simulation tool that is run on desktop computers.

Beach-*fx* relies on user populated databases that describe the coastal area under study, the environmental forcing in the form of a suite of historically-based plausible storm events that can impact the area, an inventory of infrastructure that can be damaged, and estimates of morphology response of the anticipated range of beach profile configurations to each storm in the plausible storm suite, together with damage driving parameters for erosion, inundation, and wave impact damages. The model is data driven in that all site-specific information is contained within the input databases, which generalizes the model and makes it easily transportable between study areas. Beach-*fx* integrates the engineering and economic analyses and incorporates uncertainty in both physical parameters and environmental forcing, which enables quantification of risk with respect to project evolution and economic costs and benefits of project implementation.

This new model provides for a more realistic treatment of shore protection project evolution through the relaxation of a variety of simplifying assumptions that are made in existing, commonly applied approaches. Beach-*fx* is implemented with a modern graphical user interface, an interface to geographical information system data, extensive reporting and visualization, and database population tools.

The U.S. Congress has authorized federal participation in hurricane and storm damage reduction projects to prevent or reduce damages caused by coastal storms that produce elevated water levels, storm waves, and coastal erosion. Responsibility for the design, construction and maintenance of federally authorized shore protection projects lies with the U.S. Army Corps of Engineers (USACE) as part of its civil works mission. Federal shore protection projects are designed to provide protection for existing infrastructure against erosion, inundation and wave attack damages. Typically, only those projects for which the benefits exceed the costs are considered for construction. Local entities participate in the planning and share the costs of planning, construction, and maintenance of the project with the federal government.

ADDITIONAL KEYWORDS: Beach nourishment, economic analysis, storm damage reduction, risk analysis, U.S. Army Corps of Engineers, planning, simulation, Monte Carlo.

By regulation, the analysis involves the estimation of the benefits and costs of different alternative projects and scales of alternatives over a life cycle evaluation period, typically 50 years. Project benefits are obtained as the difference between expected damages with the project in place and expected damages in the absence of a project. Project costs are obtained as the estimated additional life cycle costs associated with project implementation and maintenance. Note that the "without project" alternative is not typically a "no cost" alternative because, along an eroding coast, land owners will ultimately have to make investments to protect their property through armoring to avoid loss of the property. In addition, in most jurisdictions, other protective actions such as emergency dune construction or limited local shore protection projects will be constructed subsequent to major losses after a storm or in anticipation of catastrophic losses when the upland infrastructure becomes vulnerable.

A proper economic analysis must take into account the stochastic nature of storm-associated damages; that is, the variability related to the occurrence, intensity and sequence of storms and the impact of those storms on beach morphology change and near-shore structures (USACE 2000). Storm-induced damages to a given structure are a function of structure location and character (foundation type, construction type, elevation, etc.), storm intensity (total water elevation, maximum nearshore wave height, induced beach erosion, etc.), storm timing, and the degree of protection provided by the natural or constructed beach. Thus, the analysis requires a combination of meteorology, coastal engineering, and economic analyses. Furthermore, the analysis must have the capacity to trigger various reactive actions based on the occurrence of previous events. An example would be triggering of emergency dune construction after occurrence of a major storm that effectively eliminated the dune feature.

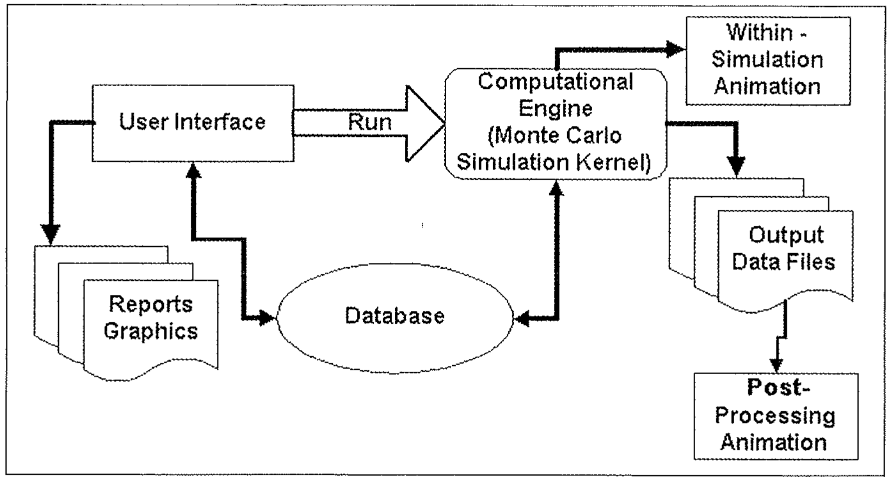
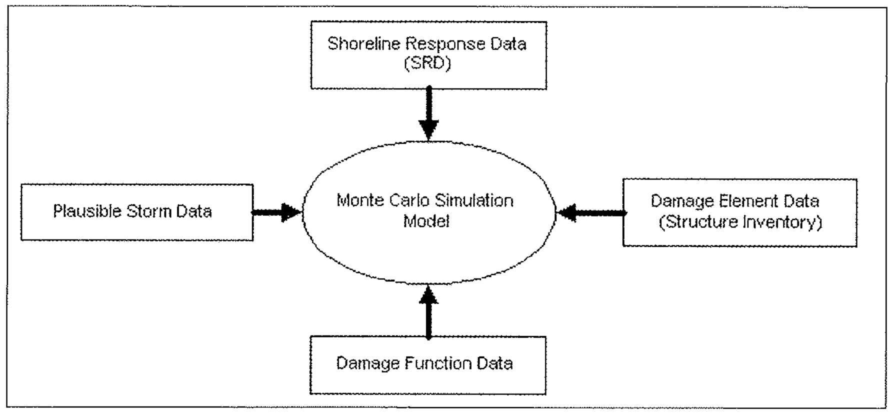


Figure 1. Beach-*fx* computational architecture.

Figure 2. Elements of the Beach-*fx* input database.



In recognition of these issues and the requirement for careful analysis, the U.S. Army Engineer Institute for Water Resources (IWR) and the U.S. Army Engineer Research and Development Center's Coastal and Hydraulics Laboratory (ERDC-CHL) have collaborated on the development of a new framework for performing engineering-economic analyses associated with storm damage reduction studies. The product of this research is the Beach-*fx* Monte Carlo simulation model. This new model provides an event-based framework that replaces older frequency-based analyses that are derived from riverine flooding approaches, which are not as suitable for the coastal storm damage problem. The new approach has been implemented as a non-proprietary desktop computer model that better captures the true dynamic evolution of beach nourishment projects and provides means of quantifying uncertainty associated with both project performance and economic consequences of project implementation through Monte Carlo life cycle simulations. The model is oriented towards analysis of sandy beaches, typical of open ocean and Gulf coasts of the United States, and towards shore protection projects that emphasize beach nourishment, although the model structure is adaptable to other situations (e.g. bluff erosion) and management measures, such as land use zoning or buy-out programs.

Beach-*fx* is a planning-level tool used to evaluate proposed project alternatives in comparison with a similar evaluation of the "without-project" condition. Other potential uses include application of Beach-*fx* to quantify, with uncertainty, the damages prevented by an existing shore protection project due to a specific storm or storm season. A companion paper in this issue describes one such application. The model can also be used to examine the economic justification of post-storm reconstruction activities. That is, to help answer the question, from a risk-based perspective, if it is more appropriate to immediately restore a shore protection project to pre-storm conditions after the passage of a major storm event or to wait until the next scheduled renourishment activity. A life cycle analysis, typically over a 50-year time horizon, is necessary because of the relatively infrequent occurrence of damaging storm events in an area, i.e. high consequence, low probability events. Multiple iterations of a 50-year life cycle are necessary to capture the variability of estimated damages.

Beach-*fx* employs an event-driven Monte Carlo approach that incorporates probabilistic seasonal storm generation, beach profile response to storms, shoreline change driven by long-term coastal processes, beach management activities, and structural damage and economic effects associated with inundation, erosion and wave attack. The model improves upon previous models in this arena by being strongly based on representation of coastal processes, incorporating the impact of multiple storms, and including a time-varying representation of the beach profile and improved treatment of uncertainty in structural parameters, storm-induced damages, and structure and content valuations. Assumptions upon which Beach-*fx* is based are explicit, and the model has been designed for transparency in that its detailed workings are clear, through animation and visualization of predicted behavior and generation of detailed outputs.

MODEL OVERVIEW

Beach-*fx* is comprised of four basic elements:

- Meteorologic data and processes.
- Coastal morphology change data and processes.
- Economic data and processes.
- Management measures data and processes.

Beach-*fx* is a data-driven model, in that the data elements are stored in a relational database, whereas the process descriptions (rules for applying the data

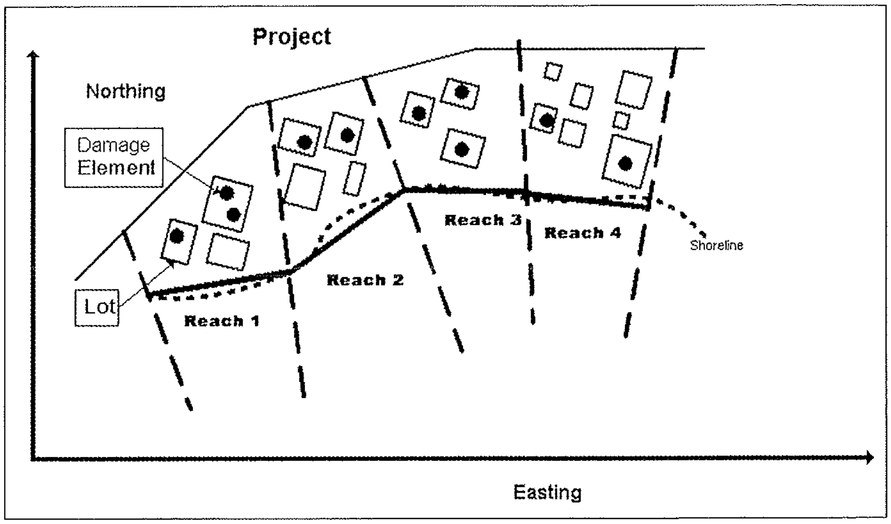


Figure 3. Beach-*fx* schematization of the project study area.

elements) are embodied in the program itself (the computational engine). This general architecture is shown in Figure 1. The user interface covers data input, editing, and manipulation, as well as reporting and visualization of results. The computational engine reads the databases, performs the necessary simulation, writes output files and places output information back in the appropriate databases for additional reporting and visualization.

The databases that provide the necessary input to run Beach-*fx* contain a full description of the coastal area under study, a suite of historically-based plausible storms that can impact the area, an inventory of structure elements that can be damaged, and the estimated morphology response of the anticipated range of beach profile configurations to each storm in the plausible storm suite, together with a cross-shore varying profile of damage-driving parameters for estimating inundation, erosion and wave impact damages. This architecture allows the model to be readily transportable between study areas, as the specification of the project area is contained in the input databases.

At present, the beach profile responses to storms in the plausible storm suite are estimated using the SBEACH model (Larson and Kraus 1989) to calculate the response of the profile to individual storms, and the GENESIS model (Hanson and Kraus 1989) to provide estimates of the long-term shoreline change as well as project-induced shoreline change produced by alongshore spreading of the nourishment project. However, because the input databases used by Beach-*fx* are pre-computed, alternative coastal process simulation models could be employed to populate the storm and long-term beach morphology change components of the database. Figure 2 provides a schematic illustration of this architecture.

PROJECT AREA REPRESENTATION

The overall unit of analysis is the "project," a shoreline area for which the analysis is to be performed. The project is divided, for purposes of analysis, into "reaches," which are contiguous, morphologically homogeneous areas. The structures within a reach are referred to as Damage Elements (DEs), and are located within lots. All locations are geospatially referenced using a cartographic coordinate system such as state plane coordinates. This project definition scheme is shown schematically in Figure 3, in which the shoreline is linearized into reaches. Each reach is associated with a representative beach profile that describes the shape of the cross-shore profile and beach composition. Thus, within a project, multiple reaches can share the same representative beach profile.

The profile is the basic unit of beach response. Natural beach profiles are complex; for the modeling, a simplified beach profile, representing key morphological features defined by points, is used, as shown in Figure 4. The simplified profile represents a single trapezoidal dune, with a horizontal berm and a horizontal upland landward of the dune feature. The submerged portion of the profile is represented by either a detailed series of points, or an approximate functional representation known as the equilibrium profile (Dean 1977). Some of the values of the simplified profile are taken as constant, not varying with storm response or management measures. The beach profile variables that may be changed by storms are dune width, dune height, berm width, and upland width. The constant values are upland elevation, dune slope, berm elevation, foreshore slope, and the shape of the submerged profile. Thus, in response to a storm, the berm can erode or accrete (change in berm width); the dune can change height and/or width, and can translate landward resulting in an upland width change.

METEOROLOGICAL DATA AND PROCESSES

Beach-*fx* internally generates a synthetic sequence of storms for each life cycle simulated. This set of storms is the primary driving force for coastal morphology change and associated damages.

The eastern and Gulf coasts of the United States are subject to tropical storms (hurricanes), and the east coast is also subject to extra-tropical storms (northeasters). Both types of storm are seasonal. The storm climatology in a given area is site-specific. Beach-*fx* makes use of a set of "plausible storms" that are derived from the historical record in the study area. The synthetic sequence of storms that make up the simulated life cycle is obtained by performing a bootstrap sampling with replacement on the plausible storm suite. The historical storm record is extended to the plausible storm suite by assuming that the historical storm could have occurred at various combinations of tidal phase and tidal range, other than the one at which it actually took place, such that for each historical storm 12 plausible storms are generated. This is achieved by combining the historical storm surge hydrograph with 12 possible variations of the astronomical tide. The peak of the storm surge hydrograph is combined with the astronomical tide at high tide, mean tide falling, low tide and mean tide rising for each of three tidal ranges, corresponding to the lower quartile, mean, and upper quartile tidal ranges. This is usually accomplished by numerical estimation of the storm surge hydrograph in the absence of tides.

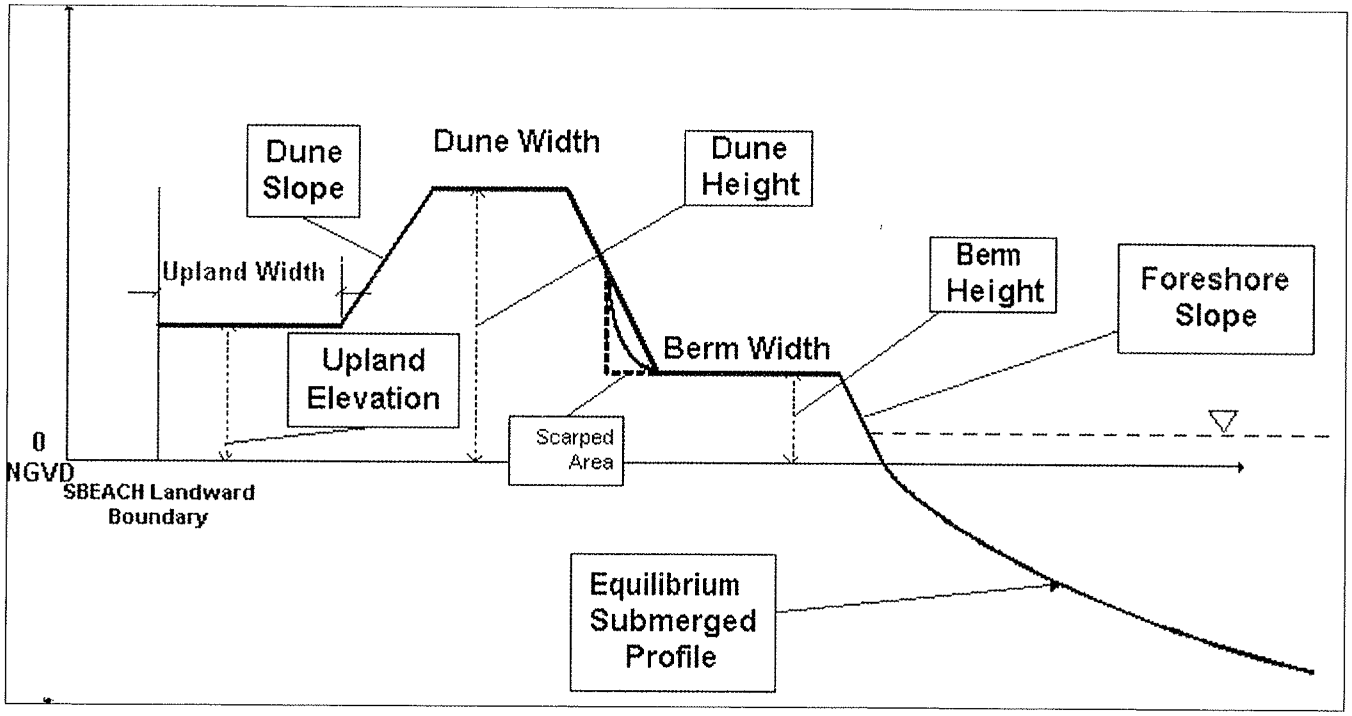


Figure 4. Beach-*fx* simplified representative beach profile.

The astronomical tides are typically approximated with an idealized cosine tide with amplitudes obtained from a statistical analysis of the tidal record at the site.

The user defines the desired storm seasons (up to 12 seasons can be defined) based on storm seasonality at the project site, and each plausible storm is assumed to take place within the season in which the original historical storm occurred. Storm seasons for different storm types (hurricanes and northeasters) can overlap such that both types of storms could take place during the same period of time. The probability of both tropical and extra-tropical storms is defined for each season. Based on this assigned probability, a Poisson distribution is used to determine the number of storms of each type that will occur in the season. The Poisson distribution is used because it expresses the probability of a number of events occurring in a fixed period of time assuming that the events occur with a known average rate, and are independent of the time since the last event.

Once the number of storms is known, the second step of the bootstrap process randomly selects that many storms from the sub-set of plausible storms of that type that fall in the season being processed. For each storm selected, a random time within the season is chosen and assigned as the storm date. After the first storm date is chosen, the date assignment routine attempts to preserve a user-defined minimum storm interarrival time for subsequent storms, to maintain separation between storms. For example, if a seven-day interarrival time is specified then the algorithm will attempt to place the second storm in the season outside of a 14-day window surrounding the date of the first storm. Maintaining this separation is not always possible, and Beach-*fx* reports any violations of the interarrival specification.

COASTAL MORPHOLOGY CHANGE DATA AND PROCESSES

Beach-*fx* is based upon a simplified beach profile morphology and plausible storms developed as time series of wave height, wave period, and total water elevation. The beach profile response due to a plausible storm is determined by applying a "coastal process response" model to a simplified profile. Although alternative coastal process response models could be used, the beach profile response model that has been employed with Beach-*fx* is SBEACH (Larson and Kraus 1989), a numerical model for simulating storm-induced beach change. SBEACH takes as input the storm time series and the initial profile definition, as well as other descriptors of the beach (e.g., grain size) and model parameters, and produces as output, the estimated beach profile at the end of the storm, as well as cross-shore profiles of erosion, maximum wave height, and total water elevation including wave setup. This information is extracted from the SBEACH output by post-processing routines and stored in the Shore Response Database (SRD), a relational database used to prestore results of SBEACH simulations of all plausible storms impacting a pre-defined range of anticipated beach profile configurations, as defined by ranges of berm width, dune width, and dune height.

The SRD is site- and study-specific; that is, it is developed uniquely for each shore protection project study area. Two kinds of results are stored in the SRD for each storm/profile combination: changes in berm width, dune width, dune height and upland width, and the cross-shore profiles of erosion, maximum wave height, and total water elevation. The morphology changes (berm width, dune width, dune height and upland width) are used to modify the simplified pre-storm beach profile to obtain the post-storm profile. The damage driving parameters (cross-shore profiles of erosion, maximum wave height, and total water elevation) are used in the estimation of damages to DEs within reaches associated with that representative profile. The SRD is thus a pre-generated set of beach profile responses to storms, for the plausible storms developed previously, and for a range of profile configurations that are expected to exist under different scenarios of storm events and management actions (beach nourishment).

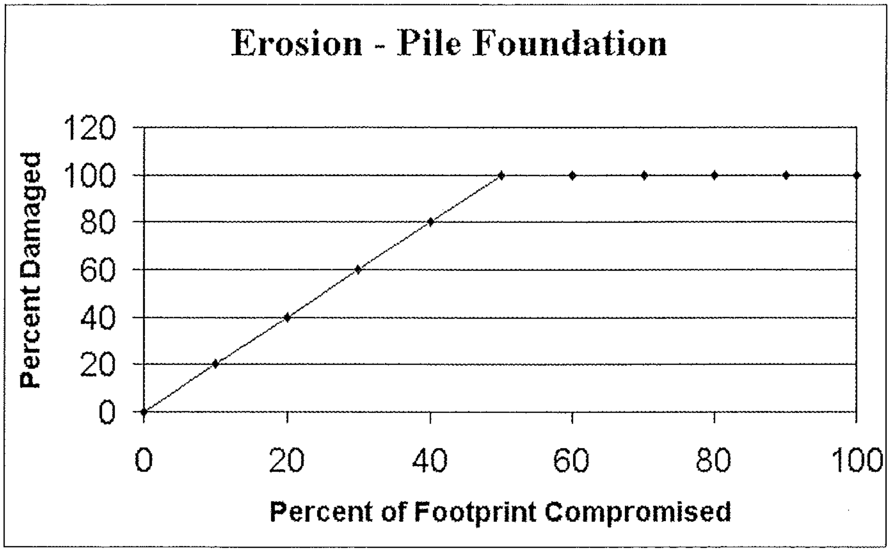


Figure 5. Typical damage function for estimating erosion damage.

The Beach-*fx* development team determined that use of the SRD was necessary because it did not appear feasible or desirable to run SBEACH "in-line" with the Monte Carlo simulation model due to computational and data specification considerations. Furthermore, designing Beach-*fx* to rely on a pre-computed SRD allows for the potential use of alternative coastal process models or new predictive models that may emerge in the future. The pre-computed SRD provides the mechanism by which Beach-*fx* obtains morphology response and damage-driving parameters for all possible combinations of the plausible storm suite and beach profile configurations encountered throughout any given life cycle simulation.

The SRD, once generated, serves as a look-up table by the Monte Carlo simulation model. The Monte Carlo simulation has available to it the same set of storms used in populating the SRD. As a given storm from the simulated sequence takes place, the current profile (defined by representative profile, dune width, dune height and berm width) is used to look up the results that are associated with that storm in the SRD for the profile that is closest to the pre-storm profile as tracked in the simulation. These results then define the post-storm profile to track volume changes and to determine within-storm erosion, and wave heights and water elevations associated with the storm along the cross-shore profile.

Storm-based morphology change includes a representation of scarping of the seaward dune face. Dune scarping takes place when the berm retreat is calculated to invade the seaward toe of the dune. The user provides, as input, the height above the berm elevation that results in non-recoverable dune scarping. The concept is that scarping low on the dune face will recover over time as does the berm width. However, dune scarping that extends high on the dune face will not recover and, if scarping exceeds the user specified maximum recoverable scarping elevation, the dune width (and dune elevation, if necessary) is reduced by equating the predicted berm volume loss to volume loss in the dune section, to obtain the post-storm profile. An ordered set of volumetric equations is defined for the evolution of the beach profile, such that berm width is first reduced to zero, then when maximum recoverable scarping is exceeded, the dune width is reduced until the dune is triangular, at which point the dune height is lowered until it intersects with either the upland elevation or the berm elevation, whichever is highest.

In addition to storm-induced morphology changes, Beach-*fx* provides for three other mechanisms for morphology change:

- An applied shoreline change rate;
- Project-induced shoreline change rate; and
- Post-storm berm width recovery.

The user-specified applied shoreline change rate is a reach level calibration parameter and is specified in feet per year, for each reach. The applied shoreline change rate is set so that the combination of the applied shoreline change rate and storm-induced change returns the historical shoreline change rate for the reach. The target historical shoreline change rate is determined based on a separate analysis of the available historical beach profile and/or shoreline position data. The calibration procedure causes Beach-*fx* to return, on average, over hundreds of iterations of the 50-year analysis horizon the historical shoreline change rate. Therefore, although the resulting rate of shoreline change for any given life cycle simulation may vary considerably from the historical rate of shoreline change, the average rate of shoreline change over hundreds of life cycle simulations is equal to the target historical shoreline change rate.

The project-induced shoreline change rate, also in feet per year, accounts for the alongshore dispersion of the placed beach nourishment material. Estimates of the project-induced shoreline change rate are obtained through application of a one-line shoreline change model such as GENESIS (Hanson and Kraus 1989). Project-induced shoreline change rates are computed for each of the planned beach nourishment cycles, which accounts for the improved performance of beach nourishment projects that comes with project maturation. That is, theory and beach nourishment experience has shown that dispersion losses at a beach nourishment project tend to decrease with the number of project renourishments. This information is stored in the database by reach and nourishment cycle.

Within the simulation the applied project-induced shoreline change rate changes with nourishment cycle as determined from the one-line shoreline change model results. Both the applied shoreline change rate and the project-induced shoreline change rate act to modify the beach profile berm width and are applied at a user-specified time step interval. Post-storm recovery of eroded berm width after passage of a major storm is recognized by the coastal engineering community although the present state of coastal engineering practice has not yet developed a predictive capability for estimating this process. Consequently, within Beach-*fx*, post-storm recovery is represented in an ad hoc procedure in which the user specifies the percentage of the estimated berm width loss during the storm that is recovered over a user specified recovery interval.

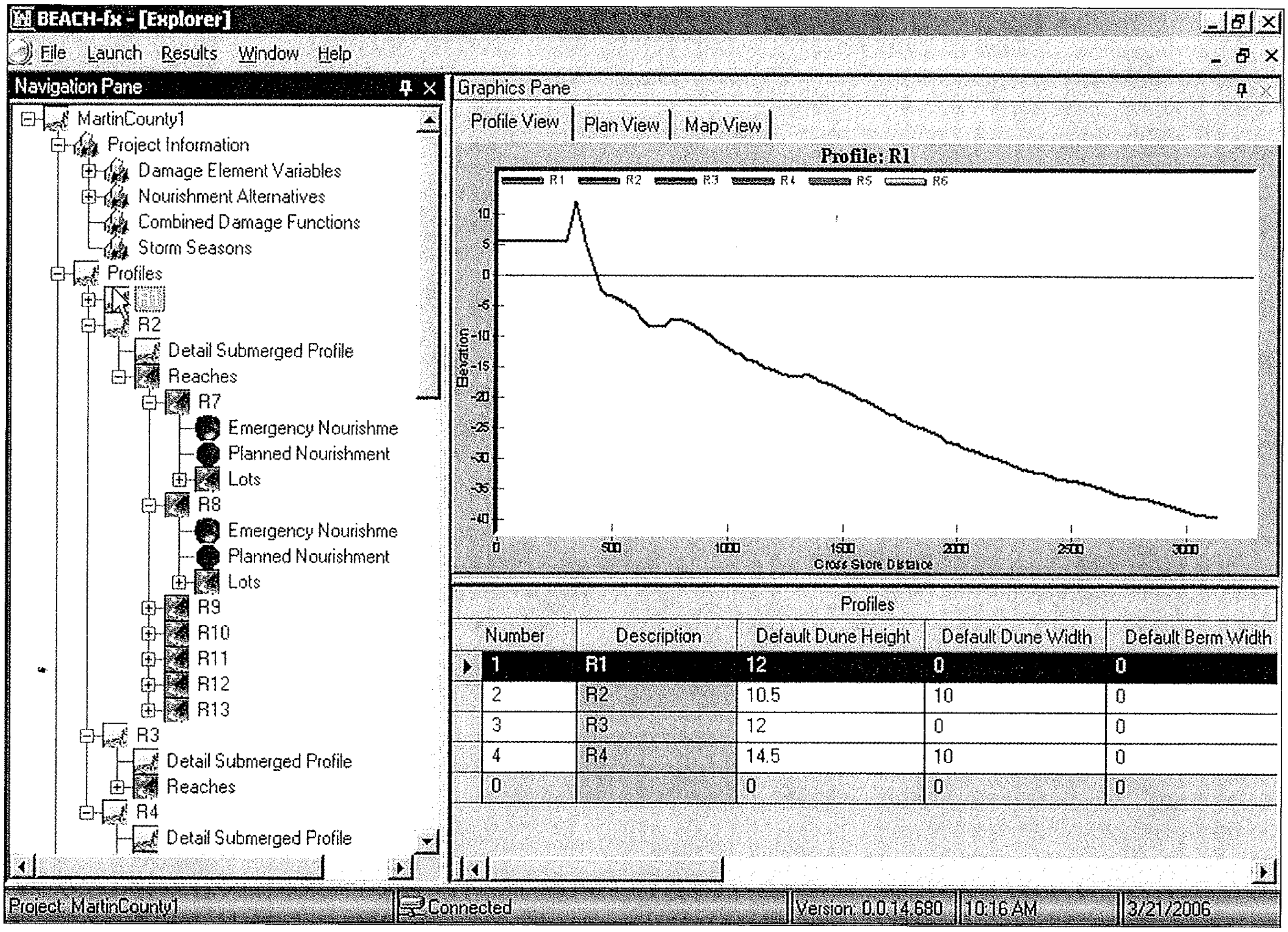


Figure 6. Beach-*fx* user interface screen.

ECONOMIC DATA AND PROCESSES

A proper economic analysis of shore protection projects must take into account the probabilistic nature of storm-associated damages to structures. This damage is a function of structure location and character, storm intensity, storm timing and the degree of protection that is provided by the natural, or constructed, beach. Damage is caused by:

(1) Erosion, which can result in structural failure due to loss of foundation support;

(2) Flooding by elevated still water level;

(3) Wave impact (kinetic forces); and

(4) Wind associated damage.

The model presently represents the first three types of damages; wind damage is not included, because shore protection projects do not mitigate wind damage.

Following each storm, damages are calculated for each reach, lot and damage element (a generalization of the term "structures"). Each damage element (DE) is geographically referenced, and characterized as to usage, construction type, foundation type, value of contents, value of structure and ground and first floor elevation. The storm determines the water level, maximum wave height, and erosion profiles, which are obtained from look-ups in the SRD. These response profiles exist at the representative profile (and thus the reach) level and are defined in the cross-shore, such that erosion, flooding, and wave damage can vary depending upon the location of the DE within the reach. These values are then used to calculate damage-driving parameters for each DE.

The general approach to damage estimation is that developed in an expert elicitation workshop, the Coastal Storm Damage Workshop (CSDW), conducted by the U.S. Army Corps of Engineers (USACE 2002). This approach requires the calculation, for each DE, of a damage-driving parameter, based on the DE characteristics (location, elevation, foundation type). For example, a damage-driving parameter for erosion for a pile foundation is the percent of footprint compromised; that is, the percent area of the DE footprint for which erosion exceeds a designated threshold. The relationship between the value of a damage-driving parameter and the percent damage incurred is expressed as a user-entered "damage function," similar to that shown in Figure 5.

Damage functions are user-specified and can vary based on the type of construction, foundation type, etc. Functions are defined separately for structure and contents. Each such function gives a percent damage as a function of the damage driving parameter. To represent uncertainty, the CSDW expert elicitation defined three damage curves of the type shown in Figure 5 for each situation as a lower, most likely, and upper curve. This allows for the creation of a triangular distribution based on interpolation across the three curves and then the triangular distribution can be sampled to return a value of percent damage. Consequently, three values are available in the form of percent damage caused by inundation,

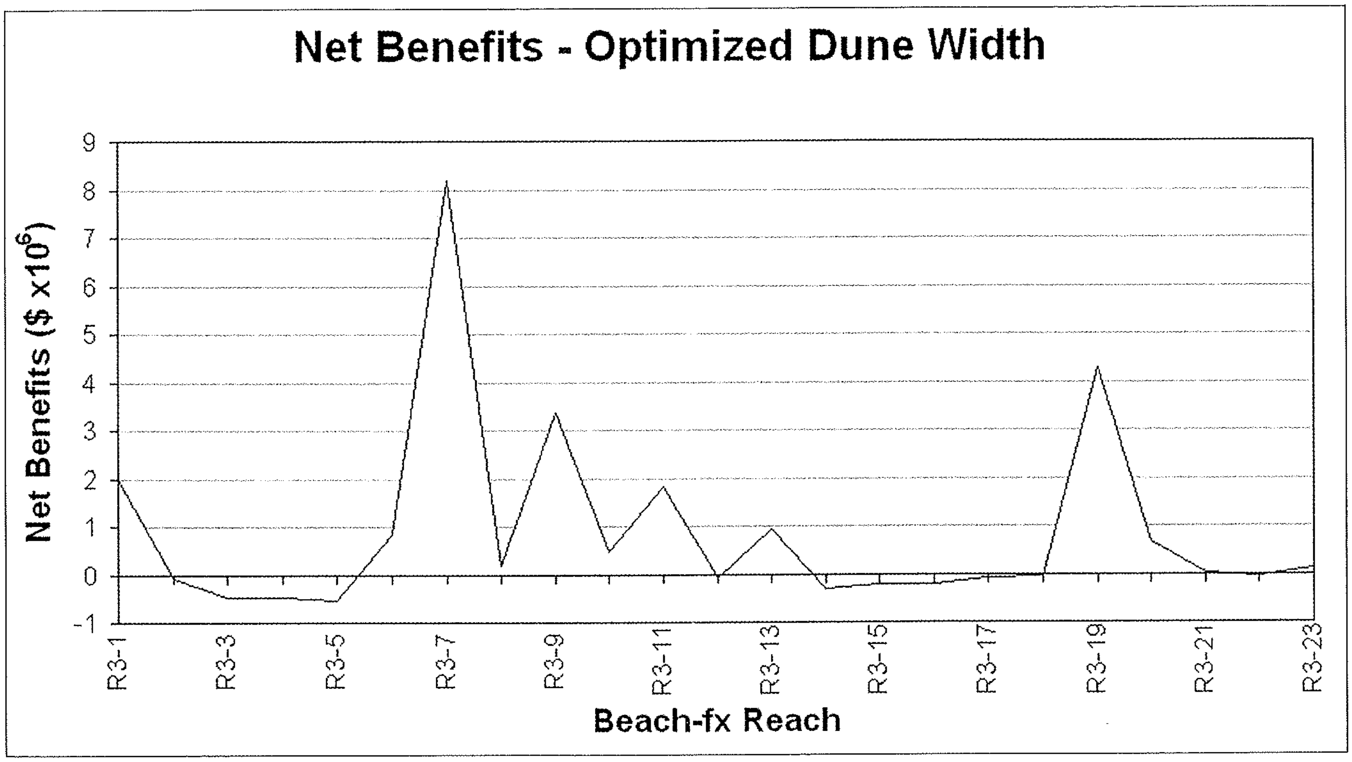


Figure 7. Net benefit associated with alternative planned nourishment.

erosion, and wave attack. Damages due to inundation, erosion, and wave attack are then used to calculate a combined impact according to the methodology of the CSDW, to avoid double-counting of damages. The combined damage impact reduces the current value of the DE. The total of all damages (reductions in value) is the economic loss that can be mitigated by the shore protection project. DEs can be rebuilt or, if the shoreline has encroached too far into the lot, the lot can be declared condemned (or unbuildable), such that no rebuilding can take place.

Beach-*fx* generates detailed output that provides the value history of each DE through the simulation as it is damaged by a storm and possibly rebuilt, as well as summaries of damages for each reach by year and damage element type (single-family residential, walkway, pool, etc.).

MANAGEMENT MEASURES DATA AND PROCESSES

Management measures provided for in Beach-*fx* are emergency nourishment and planned nourishment. Emergency nourishment occurs when local government takes post-storm action to perform limited beach nourishment by adding volume to the existing profile. Planned nourishment is a proactive measure, in which a designed beach nourishment program is implemented at a regular interval, to build the reach profile to a defined design template.

Within Beach-*fx*, different emergency nourishment and planned nourishment alternatives can be set and a simulation run with the selected alternatives. For emergency nourishment, an alternative is based on reach-level triggers that will result in emergency nourishment of the reach, based on minimum thresholds of dune height, dune width, or berm width, which if met will result in an emergency nourishment action. The action is specified as a possible placement volume, in cubic yards per foot of beach, that will be placed. Other user-entered parameters include the unit placement cost, production (placement) rate, and borrow-to-placement ratio, such that costs of emergency nourishment can be estimated.

Planned nourishment is similarly user specified based on design templates, triggers, and nourishment cycles. Nourishment cycles are defined as periodic (e.g. every three years). An order of reach nourishment is defined in the database, as well as reach-level design templates (dune width, dune height, and berm width), and placement rates, unit costs, and borrow-to-placement ratio.

At the specified nourishment interval, all reaches to be nourished are examined to determine if mobilization is warranted. The existing reach profile is compared to the design template and, if the needed nourishment volume (on the basis of the entire project) exceeds a user-specified threshold volume at which the mobilization cost (a fixed value) is deemed justified, then mobilization and nourishment take place. Then on a reach-by-reach basis, if nourishment is required the nourishment time is determined based on placement rates. A start nourishment and end nourishment event for the first reach are created. At the end of the nourishment, the reach profile is set to the design template, and the next reach in processing order is examined to see if nourishment is required. The process continues until all reaches have been covered. The total cost of the nourishment action, including mobilization and placement costs, is then calculated.

USER INTERFACE AND OUTPUTS

The user interface allows for data editing, entry, and viewing of the large amount of information utilized by the model. A three-pane approach, as shown in Figure 6, provides for an explorer window to select any element from the hierarchy of profile, reach, lot and damage element; examine and edit the data in tabular form; and, where applicable, view a graphical representation of the data (profile view, plan view, and a map view in which GIS shape files and aerial photographs associated with the project can be viewed).

Numerous outputs are produced by Beach-*fx*, including:

1. Output reports available through the user interface.
2. Output graphics and charts available through the user interface.
3. Checks on input data for completeness and proper geographic location.
4. Detailed outputs in the form of ASCII and Excel-compatible files, describing storm generation, storm response, damages, lot condemnation, and rebuilding.
5. Within-simulation visualization, allowing the user to watch the progress of morphology change in plan and profile views and to interrogate a damage element to determine current value, as the simulation is running.
6. Post-processing animation, based on output data files, showing 2-D and 3-D representations of morphology change over time.

An example of the kind of graphical display that can easily be generated from Beach-*fx* outputs is shown in Figure 7, indicating how the application of a planned nourishment alternative leads to areas of benefit and areas of increased cost, along the project shoreline. This kind of display is particularly useful in identifying those areas where the nourishment is justified on an economic basis.

APPLICATIONS

Beach-*fx* development took place first through coding the concepts and procedures discussed previously, which led to a proof-of-concept model demonstrating the feasibility of the approach. To further mature the modeling approach and model development, a test-bed application was undertaken in conjunction with a hurricane and storm damage reduction feasibility study for the beaches of Walton County, conducted by the USACE, Mobile District. This study, comprising 27 miles of shoreline, was used to test and refine many aspects of the model and model outputs. Three additional beta-test applications of Beach-*fx* are under way and include a storm-damage reduction study at Barrow, Alaska, being conducted by the USACE, Alaska District; the Mississippi Coastal Improvement Project (MsCIP) aimed at developing a comprehensive plan for hurricane and storm damage reduction along the Mississippi Gulf of Mexico shoreline in the wake of Hurricane Katrina; and a research case study investigation of the damages prevented by the federal shore protection project at Martin County, Florida, during the 2004 tropical season. The MsCIP project is being performed by the USACE, Mobile District, with technical assistance being provided by ERDC-CHL. The shore protection assessment research program managed by ERDC-CHL funded the case study analyses at Martin County and a companion paper in this volume of *Shore & Beach* provides a summary of the findings of that investigation.

CONCLUSIONS

Beach-*fx* was developed in an attempt to incorporate the best current practicable knowledge on coastal engineering processes in order to perform economic evaluations of federal hurricane and storm damage reduction projects under a risk and uncertainty framework. The problem is enormously complex. Development of Beach-*fx* as a process-driven model has served to clarify areas where there are data gaps (for example damage functions for all types of structures) or gaps in knowledge (post-storm berm recovery) relating to overall system behavior.

The authors believe that Beach-*fx* represents a competent and useful technical framework and approach to studies of this kind, in that it incorporates the inherent risk and uncertainty that is associated with shore protection, is strongly driven by the coastal processes that are represented, combines both engineering and economic behavior, and is constructed as a data-driven transparent model, in which behavior is evident. As a Monte Carlo simulation model, Beach-*fx* produces not simply point estimates and averages, but also the ranges and distributions of behavior that may be expected to occur.

Beach-*fx* will continue to be improved and enhanced to expand its applicability and to develop efficient procedures and protocols for developing the extensive input data sets needed to run the model, through the Flood and Coastal Storm Damage Reduction Research Program managed and executed by ERDC-CHL. Beach-*fx* is presently undergoing certification as part of the USACE Planning Model Improvement Program being managed and executed by IWR.

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Development of Beach-*fx* required collaboration of many individuals and groups, both within the USACE and outside experts. In particular, the authors would like to acknowledge the individuals who participated and contributed to the Coastal Storm Damage Workshop, the field review team that provided conceptual guidance on how shore protection projects are managed and executed, the team of contractors led by CDM Inc. of Carbondale, IL, that faithfully coded the procedures that make Beach-*fx* the valuable tool that it is, and the Hurricane and Storm Damage Reduction Center of Expertise that has provided practical guidance and direction throughout the development of Beach-*fx*. Permission was granted by USACE headquarters to publish the information contained in this paper.

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