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A Discussion of the Generalized Model for Simulating Shoreline Change (GENESIS)

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ABSTRACT

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The Generalized Model for Simulating Shoreline Change (GENESIS) (HANSON and KRAUS, 1989) is designed to simulate the long-term shoreline changes at coastal engineering sites resulting from spatial and temporal differences in longshore sediment transport. GENESIS is used by the coastal engineering and planning communities for predicting the behavior of shorelines in response to coastal engineering and/or beach replenishment activities that may alter longshore transport. GENESIS is also used by some modelers to develop regional scale sediment budgets. We have evaluated the assumptions behind the GENESIS model in light of well understood nearshore, geologic and oceanographic phenomena. In most cases, the assumptions used in the model fail to be met or are so oversimplified that the model's effectiveness as a predictive tool is limited at best.

In addition, the GENESIS Technical Reference (HANSON and KRAUS, 1989) makes it clear that adequate data for running the model are seldom, if ever, available. Frequently, averaged values must be used, smoothing over great potential variability in data sets (waves, profile shape, *etc.*). When predictions are made, it is not possible to quantify the uncertainty in the assumptions or the error in the data, and thus it is not possible to quantify the uncertainty in predicted results. GENESIS does not provide the modeler with statistical answers. The best the modeler can do is to vary the input parameters to produce a range of possible scenarios. There is no way to objectively evaluate which scenario is the most reasonable. As the *Technical Reference* emphasizes, even with GENESIS the user must still constantly rely on his or her own technical expertise. All of this uncertainty makes GENESIS, at best, a qualitative, not quantitative model, and at worst a model that, after a certain amount of assuming and adjusting input parameters, produces a result that the coastal "expert" employing its services expected--a way of backing up one's judgment with what appear to be real numbers. We believe that future modeling efforts need to focus on statistical models where each parameter input into the model is accompanied by probabilities of its accuracy and predictive capabilities, producing probabilistic results.

ADDITIONAL INDEX WORDS: *Sediment transport, shoreline erosion, shoreface, mathematical models*

INTRODUCTION

Shoreline change models such as SBEACH (LARSON and KRAUS, 1989) and GENESIS (HANSON and KRAUS, 1989) are increasingly being used as fundamental tools in coastal engineering project design and as a basis for determining project economic feasibility. This paper presents a detailed evaluation of the assumptions and uncertainty behind one model, GENESIS, to assess how well the model's assumptions correspond to recognized geologic and oceanographic principles of nearshore processes and to examine the model's efficacy as a predictive tool. The practical application of this objective is to determine whether GENESIS can predict the behavior of beach/shoreface sand accurately enough to warrant its use in detailed coastal engineering project design and cost/benefit analysis. For example, in the design of the Folly Beach, South Carolina replenishment project, GENESIS was used to reduce the amount of material required for initial construction by more than half, significantly reducing the cost/benefit ratio and allowing the project to go ahead (USACE, 1991). It is this kind of usage of GENESIS as a basis for increasing project feasibility that we are particularly interested in evaluating.

INTRODUCTION TO GENESIS

The Generalized Model for Simulating Shoreline Change GENESIS (HANSON and KRAUS, 1989) is used by coastal engineers to predict shoreline change resulting from spatial and temporal gradients in longshore sediment transport associated with coastal engineering projects. Shoreline change produced by cross-shore sediment transport, such as that associated with storm events, is not con-

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sidered and cannot be simulated by GENESIS. Cross-shore transport is assumed by the model developers to average out over the long term (sand moved offshore during a storm always returns during fair weather). HANSON and KRAUS (1989) state, "The model is best suited to situations where there is a systematic trend of long-term change in shoreline position, such as shoreline regression downdrift of a groin or jetty and advance of the shoreline behind a detached breakwater."

Longshore sediment transport in GENESIS is generated by waves and, in the model, "spatial and temporal differences in the transport rate may be caused by such diverse factors as irregular bottom bathymetry, wave diffraction, boundary conditions, line sources and sinks of sand, and constraints on the transport (such as produced by seawalls and groins)" (HANSON and KRAUS, 1989). The longshore extent of a typical model reach can be 1 to 100 km, and the time-frame of the model can be 1 to 100 months. The model can also accommodate shoreline movement produced by user-specified discrete events such as beach fills, river sediment discharge, and sand mining.

GENESIS is a "generalized" model in that it may be applied to any stretch of shoreline. The user, working through the model interface, specifies a number of external variables specific to that particular stretch of shoreline and may add a variety of nearshore coastal engineering structures to be tested, without having to alter the program code or without having a detailed knowledge of the internal structure of the program. The program is easily obtained from the U.S. Army Corps of Engineers and it is relatively simple for someone with nominal computing experience to run. Individuals with diverse backgrounds and with different levels of knowledge of coastal processes can apply GENESIS to complex coastal engineering problems. While this may seem to be a positive feature of the model, we believe it to be a negative feature because it allows those with limited coastal experience to produce what they believe to be authoritative results which they lack the expertise to evaluate. Nevertheless, GENESIS is being widely used by the coastal engineering community (public and private) as a tool for siting coastal engineering structures and for beach replenishment project design associated with such structures (as in the Folly Beach example above).

This paper presents an overview of the GENESIS model taken from the *Technical Reference* (HANSON and KRAUS, 1989) followed by a listing of some of the model's limitations also taken directly from the *Technical Reference*. Finally, we give a brief presentation of the insights of other modelers of complex geological phenomena and our own discussion of the GENESIS model's assumptions and uncertainty.

MODEL DESCRIPTION

This section provides an uncritical introduction to the GENESIS model taken primarily from the *GENESIS Technical Reference* (HANSON and KRAUS, 1989), the *GENESIS Workbook and System User's Manual* (GRAVENS *et al.*, 1991), and HANSON (1989). GENESIS is a complex model and space limitations allow us to discuss only the fundamental input data and model linkages.

The GENESIS model is a "one-line" model, a class of models first described by PELNARD-CONSIDERE (1956). This means that the beach/shoreface, cross-shore profile shape is assumed to remain constant as it moves landward or seaward, thus any contour may be chosen to represent the change in profile position. Typically, the shoreline represented by the wet/dry line or zero-depth contour is the designated reference point. In addition, the profile shape is assumed to be constant along the entire modeled reach and throughout the entire model run. Thus, GENESIS only quantifies changes in shoreline plan view and does not quantify changes in offshore profile shape because it assumes that there are none.

The GENESIS model requires the user to assemble a large amount of data for input into the program. Data are entered through the program's interactive interface without the necessity of altering the code. The basic physical data required to run the program include:

(1) Shoreline position
(2) Wave characteristics (height, period, and direction)
(3) Engineering structures and activities (*e.g.*, the location of groins, jetties, or beach fill)
(4) Measured and calculated beach/shoreface profiles
(5) Boundary conditions and estimates of structure permeability.

These data allow the program to transform waves, evaluate the longshore transport equations, and evaluate the fundamental shoreline change equation so that the GENESIS user may calibrate, verify, and ultimately predict with the model.

Shoreline Position

The first step in preparing to run GENESIS is the establishment of a shoreline coordinate system (Figure 1). The x-axis is drawn parallel to the regional trend in the shoreline with the y-axis oriented offshore setting up a right-hand coordinate system. Next, the distance alongshore is divided into cells (called grids). The chosen grid spacing is decided based on the desired detail, computation time, and the quality or availability of the input data. Typical grid spacing is 25–100 m. All geographic information will be referenced to this coordinate/grid system.

Shoreline position is referenced to the longshore baseline (the x-axis). It may be obtained from direct shoreline surveys, air photos, charts, maps, *etc.* Shoreline position traditionally has referred to the 0-contour or wet/dry line on the beach. It is important to note that the user must gather historical shoreline data, as well as modern shoreline position data, for calibration and verification runs.

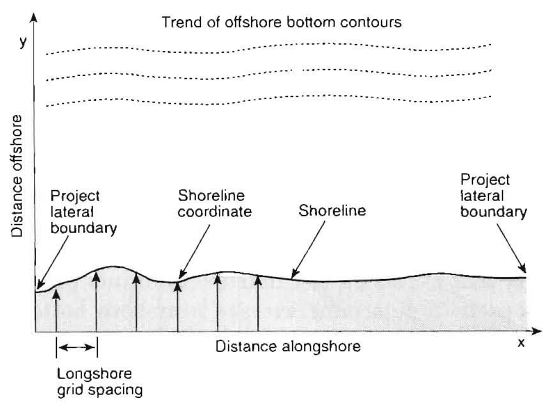

Figure 1. GENESIS shoreline coordinate system, after HANSON and KRAUS (1989).

Offshore Waves

Obtaining satisfactory wave data is both the most important and frequently the most difficult task in preparing to run the GENESIS model. HANSON and KRAUS (1989) state that "it is rare to have adequate wave gage data for a modeling effort." Most frequently, hindcasts of wave data are used such as the Wave Information Study (WIS) estimates (*e.g.*, HUBERTZ *et al.*, 1993). The least preferred data are simple statistical summaries of wave hindcasts. GENESIS can accommodate waves approaching from multiple sources.

Wave height, wave direction, and period determined from an offshore gage or hindcast point must be entered into the model at a fixed, user-specified time interval (typically 6–24 hours). Wave height and direction is then transformed from the offshore gage or hindcast point to the zone of breaking at grid intervals alongshore. The period is held constant by monochromatic wave models during this process. GENESIS may use either an internal wave transformation model or an external wave transformation model. The internal model may be used only in a "scoping" mode or when offshore contours are relatively straight and parallel. If the bathymetry is more complex, then an external wave transformation model such as RCPWAVE (EBERSOLE *et al.*, 1986) should be used. The external model will transform waves over a digitized, user-specified bathymetry until just outside the breaker line. A nearshore reference line is established at this depth contour and the externally transformed wave data are placed in a file by the modeler. The internal wave transformation model is then used to mathematically bring the waves to the breaking point and onto the beach. In all cases, the internal model will determine the breaking wave characteristics which are used to calculate the actual longshore sediment transport.

Engineering Structures and Activities

All engineering structures and activities (groins, replenishment, *etc.*) must be located on the model stretch within space and time including location, volume, and timing of beach fills. In addition, it will be necessary to specify permeability factors for structures like groins, jetties, and breakwaters (this is discussed in more detail later). These factors are estimated and adjusted during model calibration and verification.

Measured and Calculated Beach/Shoreface Profiles

If an external wave transformation model is going to be used with GENESIS, then the user must obtain/digitize bathymetric data from charts or surveys. It is important to remember that if historical shoreline changes are going to be reproduced, then charts of appropriate age should be used for digitizing. Nearshore bathymetry is ideally supplemented by measured beach profiles. Profile data are necessary for determining the height of the berm and the "closure" depth, the depth beyond which the profile does not show significant change with depth. Both of these values are used in the fundamental shoreline change equation. Closure depth is frequently estimated using the method described by HALLERMEIER (1983).

The GENESIS model does not consider the actual profile shape when calculating shoreline change, because the profile, down to closure depth, is assumed to move back and forth without changing shape. Thus, a calculated equilibrium profile is used to determine average nearshore bottom slope (used in the longshore transport equations) and the location of breaking waves alongshore. The fundamental relationship used for the equilibrium profile is that first suggested by BRUUN (1954) and then refined by DEAN (1977):

$$h = Ay^{2/3} \qquad (1)$$

where h is water depth, y is the distance offshore, and A is a scaling parameter dependent on sediment characteristics. Recognizing that calculating a profile based only on a measured grain size is not adequate, HANSON and KRAUS (1989) provide a series of templates on which to overlay measured beach/shoreface profiles in order to estimate an "effective" grain size for determination of the A value. If no profile survey data are available, the median grain size of the sand in the surf zone is used. The A value is then used to calculate the average nearshore slope (tan β) for insertion in the longshore transport equations. In addition, the calculated profile, not measured profiles, is used to determine the point of wave breaking on each grid.

Within GENESIS, the berm height and depth of closure, as well as the shape of the profile used for determining the location of wave breaking, average nearshore bottom slope, and the width of the zone of longshore transport will all remain constant alongshore. In other words, if the model has a wave breaking further offshore on one grid cell than on another or if the zone of longshore transport is wider on one grid than another, it is simply because the wave is larger on that grid cell than on the other and not because there is any alongshore variation in profile shape, slope, or depth.

Boundary Conditions, Bypassing, and Structure Permeability

The term "boundary conditions" refers to the restriction or lack thereof on the longshore transport of sand at the lateral boundaries of the project reach. GENESIS recognizes two categories of boundary conditions.

A *pinned-beach boundary* is one where there is no observable change in historical shoreline position with time. Here, it is assumed that longshore sediment transport is not restricted across the boundary. This boundary may be open, natural beach or even a seawall. A pinned-beach boundary should be placed far enough away from the project area so that changes associated with the project do not alter the nature of the boundary.

A *gated boundary* is one where the longshore movement of sand is either partially or completely restricted. A gated boundary may be a man-made structure such as a groin or jetty or it may be a natural headland that forms the edge of a natural littoral cell. The impact of the boundary on sand both entering and leaving the grid must be considered. For example, a gated boundary may allow sand to move both on and off the grid (*e.g.*, a relatively short groin). A grated boundary may also allow sand to move in only one direction (*e.g.*, a long jetty adjacent to a deep inlet may occasionally allow sand to escape over the jetty and off the grid during periods of high waves, but sand may not be able to make it across the inlet and the jetty onto the grid in the other direction).

The GENESIS model allows sand movement past a structure in two ways, sand bypassing and sand transmission. Bypassing is the sand movement around the seaward end of the structure and transmission is the sand that moves over or through a structure, usually during high wave events. Bypassing occurs if depth of the tip of the structure (D_G) (determined from the equilibrium profile equation) is less than the depth of active longshore transport (D_{LT}) at that given point for a particular time-step. The fraction of the sand being bypassed (BYP) is expressed as:

$$BYP = 1 - \frac{D_G}{D_{LT}}. \qquad (2)$$

If $D_G \geq D_{LT}$ then BYP = 0 and no sand is bypassed. A multiplier of BYP = 1 allows all of the sand to bypass. The value of BYP will fluctuate with the wave conditions because D_{LT} fluctuates with wave conditions.

Unlike sand bypassing which is calculated internally, a transmission factor must be entered for each structure based on user judgment. The factor PERM must be specified by the user with PERM = 0 indicating a structure that allows no sand transmission and PERM = 1 indicating a structure that is essentially transparent. The value of the PERM multiplier must be entered for each shore-connected structure and is based upon the best judgment of the user taking into consideration such things as the height of the structure and its landward extension. These values are frequently adjusted during model calibration.

CALCULATING SHORELINE CHANGE

Longshore Sand Transport

The GENESIS model examines shoreline change as a direct result of fluctuations in the rate of longshore transport. It is assumed that the sole variables driving longshore sand movement are the breaking wave height (H) and the angle of breaking waves with the shoreline (θ_{bs}) alongshore. All other factors are either physical constants (*e.g.*, the density of water), user-specified constants (*e.g.*, average nearshore slope), or calibration parameters. The empirical predictive expression used in GENESIS to calculate longshore transport is:

$$Q = (H^2C_g)_b\left[a_1\sin 2\theta_{bs} - a_2\cos\theta_{bs}\frac{\partial H}{\partial x}\right]_b \quad (4)$$

where H is wave height, C_g is the wave group speed, b is a subscript indicating breaking wave conditions, and θ_{bs} is the angle of breaking waves with the shoreline. The variables a_1 and a_2 are nondimensional parameters given by:

$$a_1 = \frac{K_1}{16(\rho_s/\rho - 1)(1 - p)(1.416)^{5/2}} \quad (5)$$

$$a_2 = \frac{K_2}{8(\rho_s/\rho - 1)(1 - p)\tan\beta(1.416)^{7/2}} \quad (6)$$

where K_1 and K_2 are empirical coefficients, their value is adjusted during model calibration, ρ_s is the density of sand (assumed to be $2.65 \cdot 10^3$ kg/m^3 for quartz sand), ρ is the density of water ($1.03 \cdot 10^3$ kg/m^3 for seawater), p is the porosity of sand on the bed (assumed to be 0.4), and $\tan\beta$ is the average nearshore bottom slope.

The sin term in Eq. 4 quantifies longshore sediment transport generated by incident waves breaking at an angle to the shoreline (USACE, 1984). The cos term accounts for transport generated by the longshore variation in breaking wave height (OZASA and BRAMPTON, 1980). The two calibration parameters, K_1 and K_2, are empirically estimated, and the *Technical Reference* guides the user in choosing their magnitude. In theory, adjusting the K values during calibration and verification provides the user with an empirical longshore transport equation unique to each particular project site.

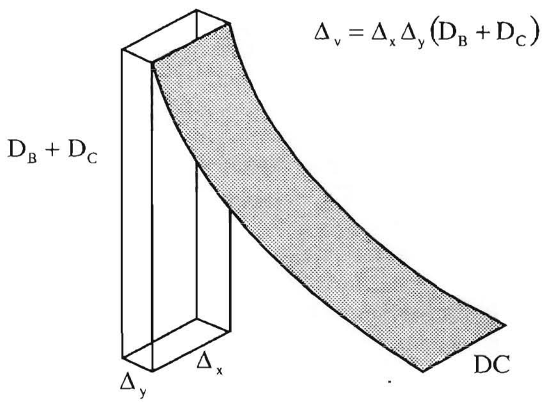

Figure 2. Definition sketch of variables in the simple relationship between volume change and shoreline change in GENESIS.

Shoreline Change Equation

The equation used to quantify shoreline change is based on the concept of conservation of sand volume. The shoreline is assumed to move seaward or shoreward without changing its profile shape in response to a net volume of sand entering or leaving a grid section. The change in volume (ΔV) of the section is given as: $\Delta V = \Delta x\Delta y(D_B + D_C)$ where Δy is the change in shoreline position resulting from the net volume change along a grid cell length of shoreline Δx with the profile moving within a vertical extent limited by the berm height (D_B) and closure depth (D_C) (Figure 2). ($D_B + D_C$) and Δx are user specified and constant; therefore, a change in volume (ΔV) of the grid section over the specified time-step results in a change in shoreline position (Δy).

Volume change in the grid section can result from a net change in the longshore transport rate (ΔQ) or from a line source or sink of sand (q) on the shoreward or seaward side. The value for q is entered by the user to account for sections of the grid where there are discrete additions or subtractions of sand. This may occur due to beach replenishment, sand mining, or any other determinable line source/sink of sediment. The user

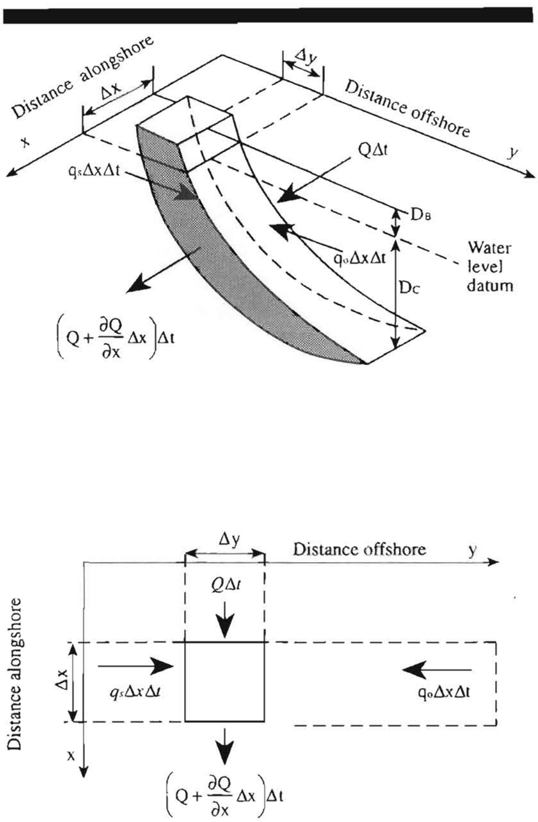

Figure 3. Definition sketch of variables in the fundamental GENESIS shoreline change equation, after HANSON and KRAUS (1989).

must specify the volume (q) and the point in time when the addition/subtraction takes place. Taking all volume change contributions into account, doing some simple mathematics, and taking the limit as Δt (time) approaches zero gives the GENESIS model's governing equation for the rate of change of the shoreline position (Figure 3):

$$\frac{\partial y}{\partial t} + \frac{1}{(D_B + D_C)}\left[\frac{\partial Q}{\partial x} - q\right] = 0. \qquad (3)$$

In a numerical model like GENESIS all of the relevant equations and variables (*e.g.*, breaking wave characteristics, longshore transport equations, shoreline change equation) are evaluated at each grid alongshore at each time-step. This way, shoreline changes are iterative.

Model Calibration and Verification

Once all data needed to run the model have been collected, the model must be calibrated verified. Model calibration refers to the process of reproducing historical shoreline change (as accurately as possible) over a given time interval while adjusting various calibration parameters, permeability factors, and while selectively adjusting the frequently inadequate wave data. Verification is the act of testing the model calibration over a different time period from the calibration interval. Frequently, some further adjustment is made during verification to fine-tune the model (as was the case in the Lakeview Park example presented in the *Technical Reference*). Proper operation of GENESIS requires that all of the data required to run the model be available for the full calibration and verification time intervals, as well as for the ultimate, predictive model run. If calibration and verification are successful, it is assumed that the model can now be used as a predictive tool for the project area.

LIMITATIONS OF GENESIS DISCUSSED IN THE TECHNICAL REFERENCE

HANSON and KRAUS (1989) list a number of model limitations, uncertainties, and warnings that should be taken into consideration before applying GENESIS.

Inadequacy of Data

(1) "It is rare to have adequate wave gage data for a modeling effort." (p. 35)
(2) "Empirically, the location of profile closure (D_C) cannot be identified with confidence, as small bathymetric change in deeper water is extremely difficult to measure. This situation usually results in a depth of closure located within a wide range of values, requiring judgment to be exercised to specify a single value." (p. 57)
(3) "Other types of data may be required in certain situations. Some of these items are difficult to quantify, such as permeability factors for groins and transmission factors for detached breakwaters; nevertheless, estimates must be made. Final values of these ambiguous quantities are usually determined in the model verification process. In these situations, special care must be given to check inferences against field data on shoreline change at the site." (p. 39)
(4) "In situations where boundary conditions are ill-defined (which is the typical situation in applications), it is of great help to monitor the net and gross longshore sand transport

rates calculated by GENESIS in addition to shoreline change." (p. 41)

(5) "In practice, data sets sufficiently complete to perform a rigorous calibration and verification procedure are usually lacking. Typically, wave gage data are not available for time intervals between available measured shoreline positions and unambiguous and complete data on historical shoreline change are often unavailable." (p. 44)

Restrictions on the Model's Application

(6) "The predictive reliability of GENESIS depends on the quality of the input data." (p. 97)

(7) "Shoreline change models are not applicable to simulating a randomly fluctuating beach system in which no trend in shoreline position is evident. In particular, GENESIS is not applicable to calculating . . . beach change inside inlets or in areas dominated by tidal flow; beach change produced by wind-generated currents; storm-induced beach erosion in which cross-shore sediment transport processes are dominant; scour at structures." (p. 19)

Need for Coastal Experience

(8) "Sophisticated models such as GENESIS should be operated by trained individuals familiar with the coast, and results should be examined in light of the observed behavior of the waves, currents, sediment movement and beach change that occur along that coast." (p. 13)

(10) "It should be cautioned that models are tools that can be misused and their correct or incorrect results misinterpreted. Ultimately it is the modeler who has responsibility for results and actions taken, not the model." (p. 15)

(11) "Given the complexity of beach processes, efforts to predict shoreline change should be firmly grounded on coastal experience, *i.e.*, adaptation and extrapolation from other projects on coasts similar to the target site." (p. 15)

Complexity of Nature

(12) "Finally, the user must maintain a certain distance from the modeling results. It should be remembered that obliquely incident waves are not responsible for all longshore sand transport and shoreline change. Potential errors also enter the hindcast of the incident waves, in representing an irregular wave field by monochromatic waves and, sometimes, through undocumented human activities and extreme wave events that have modified the beach. The probable range in variability of coastal processes must also be considered when interpreting model results." (p. 46)

(13) "However, it should be kept in mind that the assumptions are idealizations of complex processes and, therefore have limitations. In a strict sense, the assumption that the beach profile moves parallel to itself along the entire model reach is violated in the vicinity of structures. For example, the slope of the profile on the updrift or accreting side of a jetty or long groin is usually more gentle than the slope of the beach distant from the structure. GENESIS will show shoreline advance in such a case, and a calibrated model may provide agreement with measured shoreline change, but the change in beach slope and sand volume contained in that change will not be reproduced. As a result, simulations in situations where the beach slope is expected to change significantly should be interpreted carefully." (p. 49)

(14) "In light of the profound variability of coastal processes, it is clear that a single answer obtained with a deterministic simulation model must be viewed as a representative result that has smoothed over a large number of unknown and highly variable conditions." (p. 42)

These quotations taken from the *Technical Reference* point to several shortcomings in GENESIS and similar numerical models of geological phenomena: the system that GENESIS is attempting to model is highly complex with conditions that vary constantly in both time and space; even if it is assumed that the model itself is good, adequate data to perform a model run are seldom available; the model is deterministic, not probabilistic, and there is no simple, "built-in" way to evaluate model uncertainty, the modeler must constantly, and ultimately, rely on his/her own expertise.

INSIGHTS OF OTHER MODELERS OF COMPLEX GEOLOGICAL PHENOMENA

It is critical to keep in mind throughout this discussion that the GENESIS model is not just an academic exercise. This is a model that is *applied.* GENESIS is used to solve very specific coastal engineering problems and, indirectly, to compute very specific cost/benefit ratios.

Numerous researchers have attempted to model other, complex geological systems comparable to the coastal system modeled by GENESIS. It is instructive to examine some of the lessons that they have learned on the difficulties and limitations of such an undertaking. In a paper entitled "Lessons from Ten Years Experience in 2D Sediment Modeling," McAnally (1989) comments on the calibration and verification procedure used in models such as GENESIS:

> A great and harmful myth of modern modeling is the two-step calibration-verification process. Like all good myths, it is seductively appealing, particularly to those who have done little modeling other than water levels. The myth says that the modeler uses one field data set to make adjustments to model coefficients until agreement with prototype data is reached, then a second prototype data set is used to verify that the model can reproduce a different condition without changing any coefficients. When it does reproduce the second set, the model is considered to be verified. It sounds reasonable but it's wrong. The myth is wrong, and worse, it leads to poor modeling.
>
> The two-step approach is wrong because: a) verification needs more than two data sets in nearly every situation; b) it leads to misuse of available data; c) it misleads naive users into undue confidence in model results; and d) it begs the question of what to do when the second data set isn't reproduced.

Nicolis and Nicolis (1991) discuss the use of "average" values for input data in computer models. Much of the data needed to run the GENESIS model have been averaged to some degree (*e.g.*, wave data, average nearshore slope, use of a smooth equilibrium profile, *etc.*):

> Geologic materials are complex media characterized by pronounced disorder entailing that a phenomenon embedded in such a material becomes a complex process whose instantaneous rate is likely to vary continuously, depending on the locally prevailing conditions. Clearly, in light of these observations in large classes of natural phenomena, it may be meaningless to eliminate the variability and to keep only the mean as the most representative part of the behavior.

In the same volume, Franseen *et al.* (1991) declare that: "Predictions derived from model simulations are only as good as the assumptions used in the model design and model input. The range of uncertainty in these assumptions is a measure of the uncertainty of the result."

Because there is no way to measure the "range of uncertainty" in the GENESIS model's assumptions, we cannot determine the "range of uncertainty" of the results. This point severely undermines the usefulness of GENESIS as a predictive design tool and leads one to ask; What good is a predictive tool that produces an answer of indeterminable accuracy?

Recognizing that model calibration is only a limited demonstration of the reliability of the model, groundwater modelers of complex hydrological systems are already abandoning the use of terms such as "validation" and "verification." Konikow and Bredehoeft (1992) note that error in numerical groundwater models comes from "conceptual deficiencies, numerical errors, and inadequate parameter estimation." Calibration, they argue, produces a non-unique solution to the equations and verification is a "futile objective." Retaining terms like "verification" instills a false sense of confidence in the predictive capabilities of the model. In fact, hydrogeologists are producing volumes on uncertainty and reliability in groundwater modeling (*e.g.*, Kovar, 1990). This volume includes 52 papers discussing model uncertainty, model limitations, and how to adequately quantify the uncertainty so that the user can make well informed choices.

Unfortunately, the healthy academic scrutiny and debate that has surrounded the use of numerical models in other disciplines has not taken place with the major shoreline change models.

DISCUSSION

We must emphasize that we are not criticizing GENESIS as an academic undertaking. Much has been gained in many disciplines from the modeling of complex systems, nor are we disputing GENESIS' numerical accuracy (the model's ability to accurately solve the shoreline change equation). We are, however, disputing GENESIS' physical accuracy (the model's ability to reproduce real, complex physical processes), and we strongly dispute the viability of using GENESIS as a predictive tool for practical application.

GENESIS cannot legitimately be used as a predictive tool because it contains many faulty assumptions, model imperfections, and averaged values that all contribute to the uncertainty of the results in ways that are impossible to quantify or predict. GENESIS produces a representative answer, the physical accuracy of which is indeterminable by any objective standard. The following is a listing of some of the factors that contribute to model error/physical inaccuracy:

(1) Use of Averaged Values

Much of the input data are averaged values smoothing over an unquantified variability. For example:

(a) *Wave data* are the most important data in this category. Longshore transport in GENESIS is driven by wave data, and all the wave data input into the model are averaged to some extent—statistical summaries are used, monochromatic wave trains are assumed; during long runs, wave data sets are often repeated.
(b) *Equilibrium profile shape, berm height, and closure depth* are all assumed to remain constant along the entire model length and through time; and thus, an average for each must be chosen from the alongshore variation of the model reach.
(c) *Average nearshore slope* is estimated from the equilibrium profile equation and used in the longshore transport equations.

(2) Ignorance of Initial Conditions

It is impossible to perfectly measure the initial conditions for running any model. Even if the model itself were perfect, small errors in determining the initial conditions could propagate to some extent during longer model runs. Some of the initial conditions that must be quantified in GENESIS without a means of taking into consideration measurement error are:

(a) Shoreline position, initial and for all calibration and verification runs
(b) Bathymetry
(c) Berm height
(d) Closure depth (usually estimated rather than measured)
(e) Location and volume of beach fill
(f) Line source or sink of sand (q)

(3) Model Imperfections

These are imperfections in the equations that drive the model. *All* numerical models have some degree of model imperfection because no empirical equation can exactly reproduce nature. In a deterministic model such as GENESIS, the error contributed to the results from the imperfection in the equations is not quantified. Examples of imperfect equations from GENESIS are:

(a) *Longshore transport equations*: The longshore transport equations assume a uniformly sloping, sandy shoreface. PILKEY *et al.* (1993) show that the shoreface shape is strongly controlled by underlying geology and that even the assumption that the shoreface is made entirely of sand is often invalid. Another example of imperfection in longshore transport equations is that the breaking wave data used are calculated from averaged offshore wave data.
(b) *Shoreline change equation*: The shoreline change equation is a gross oversimplification. It assumes that the sand in longshore transport is spread in a thin layer over the entire shoreface. It may be argued that this has been shown to "work" in empirical model simulations, but it cannot be argued that this is physical reality.

(4) Extreme Events

GENESIS is a two-dimensional model. In the predictive mode, it cannot take into account shoreline change associated with large storms and the possible, permanent net offshore or onshore transport of sand. In fact, the model assumes the existence of a closure depth beyond which there is no net offshore movement of sand that would permanently remove sand from the longshore transport system. Yet, evidence for significant offshore transport of sand is abundant in both modern environments (HAYES, 1967; MORTON, 1981; SNEDDEN *et al.*, 1988; PEARSON and RIGGS, 1981) and from the rock record (LECKIE and KRYSTINIK, 1989; DUKE, 1990; DUKE *et al.*, 1991). Unfortunately, the frequency and severity of storms cannot be predicted; and thus, the impact that storms will have on any given model run cannot be predicted, nor can storm-induced shoreline change and subsequent beach recovery be assumed to "average out" over the long term.

The examples discussed above and numerous others not discussed contribute a certain degree of error to the results of any GENESIS model run. This error may propagate during the run in ways that are impossible to identify or to predict. While it may be possible to compensate for the error and model imperfections during a calibration run when the user knows what answer needs to be produced, this does not legitimize the use of the model for prediction.

GENESIS cannot provide the modeler with statistical answers. The best the modeler can do is to vary the input parameters to produce a range of possible scenarios. There is no way to objectively evaluate which scenario is the most reasonable. Even with GENESIS, the user must still constantly rely on his or her own technical expertise. This is emphasized both in the *Technical Reference* and in discussions that the authors have had with users of GENESIS. All of this uncertainty makes GENESIS at best, a qualitative, not quantitative model and at worst a model that, after a certain amount of assuming and adjusting input parameters, produces a result that the coastal "expert" employing its services expected—a way of backing up one's judgment with what appear to be real numbers.

DISCUSSION OF GENESIS CASE STUDIES

The strongly empirical nature of the GENESIS model is made clear in an examination of some of its applications described in the literature. The example from Lakeview Park, Lorain, Ohio given in the *Technical Reference* (Hanson and Kraus, 1989) is a perfect illustration. Here adjustments to input parameters are made not only during calibration, but also during verification. The reasoning given for adjusting some of the parameters during model verification is a lack of adequate wave data over the verification interval. Yet, it has been made abundantly clear that this will almost always be the case. This is a classic example of the "myth" of calibration and verification as described by McAnally (1989).

In an example from the northern New Jersey Shore, Kraus *et al.* (1988) found that there are not necessarily unique values for each of the input parameters. Running the model calibration with a variable depth of closure (given as a function of wave conditions), with closure depth at 1.35 m, and with closure depth at 6.0 m produced three different sets of K values, but all three scenarios did a reasonable job of reproducing the historical shoreline. This is an indication of how little physical meaning the input parameters in the GENESIS model have. Essentially, all of the input variables are calibration parameters.

Calibration of the model is not always completely successful. Simpson *et al.* (1991) describe a calibrated model for two reaches at Oceanside, California. A major shoreline feature could not be reproduced for the North Reach and the average calculated rates of erosion/accretion were off by almost a factor of two from measured rates on both reaches. If this is the best result that model calibration can produce for this stretch of shoreline when the modelers know what the end result needs to be, how can any predictive use of the model be justified.

Misuse of GENESIS is exhibited in the U.S. Army Corps of Engineers *Folly Beach General Design Memorandum* (USACE, 1991). The model run indicated that rehabilitating 9 of the existing 43 groins at Folly Beach would reduce the amount of material required for initial construction from 5.1 to 2.5 million cubic yards. This resulted in a cost reduction from $18.9 million to $11.8 million, dramatically decreasing the cost/benefit ratio and allowing the project to go ahead. These results are reported without any error bars or any indication that there is any uncertainty. Design nourishment interval was 8 years, but qualitative field observations indicate that there will be a need for major renourishment within 1–2 years. Future use of GENESIS for design of coastal engineering projects should not be allowed.

CONCLUSIONS

The authors of GENESIS state: "In light of the profound variability of coastal processes, it is clear that a single answer obtained with a deterministic simulation model must be viewed as a representative result that has smoothed over a large number of unknown and highly variable conditions" (Hanson and Kraus, 1989). We completely agree, and further postulate that "single answer" produced by GENESIS in a predictive run is of indeterminable accuracy; it cannot be objectively evaluated.

In addition to the specific criticisms previously discussed, the predictive capabilities of GENESIS and similar models suffer from the following fatal flaws: (1) We still lack a great deal of knowledge regarding the fundamental processes that GENESIS is modeling; (2) GENESIS cannot account for all the processes that move/deposit sand on the shoreface/beach; (3) Models in general have trouble when faced with systems that have a great deal of heterogeneity and non-linearity, like the coastal zone; (4) Models like GENESIS have had inadequate external peer review, testing, and quality control; (5) There is frequently inadequate expertise among those applying GENESIS to evaluate the adequacy and reasonableness of input data and results.

We suspect that we will be criticized for not having detailed in this paper a number of the predictive runs that we have performed in order to show in a more quantitative way that GENESIS is not physically accurate. We have excluded such an exercise for the following reasons: (1) We do not want criticism of this paper to center around a debate of whether or not we have applied the model correctly or whether or not we have used the best available input data; (2) We would need several years to truly test an extended predictive run, and we want the debate over the application of numerical shoreline change models to begin now.

We frequently are told by interested parties that GENESIS and models like it are the "best thing we have. Without it we have nothing!" We believe that with it we have nothing. GENESIS cannot be used for prediction in real-world situations. Our efforts should be concentrated on the development of probabilistic models for applied usages. We know that it is easier to present the public with definitive answers, but producing deterministic, physics-based, predictive models is currently beyond our reach. In the meantime, we believe that coastal experience (*e.g.*, nearby replenished beach histories) is still the best way to evaluate potential projects, especially when it comes to making hard economic decisions based on a calculated cost-benefit analysis.

LITERATURE CITED

BRUUN, P., 1954. Coastal erosion and development of beach profiles. *U.S. Army Beach Erosion Board Technical Memorandum No. 44.* U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

DEAN, R.G., 1977. Equilibrium beach profiles: U.S. Atlantic and Gulf coasts. *Technical Report No. 12.* Department of Civil Engineering, University of Delaware, Newark, Delaware.

DUKE, W.L., 1990. Geostrophic circulation or shallow marine turbidity currents? The dilemma of paleoflow patterns in storm-influenced prograding shoreline systems. *Journal of Sedimentary Petrology,* 60, 870–883.

DUKE, W.L.; ARNOTT, R.W.C., and CHEEL, R.J., 1991. Shelf sandstones and hummocky cross-stratification: New insights on a stormy debate. *Geology,* 19, 625–628.

EBERSOLE, B.A.; CIALONE, M.A., and PRATER, M.D., 1986. RCPWAVE—A linear wave propagation model for engineering use. *Technical Report CERC-86-4.* U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi, 71p.

FRANSEEN, E.K.; WATNEY, W.L.; KENDALL, C.G.ST.C., and ROSS, W., 1991. Preface. *In:* FRANSEEN, E.K.; WATNEY, W.L.; KENDALL, C.G.ST.C., and ROSS, W. (eds.), Sedimentary modeling: Computer simulations and methods for improved parameter definition. *Kansas Geological Survey Bulletin 233.*

GRAVENS, M.B.; KRAUS, N.C., and HANSON, H., 1991. GENESIS: Generalized model for simulating shoreline change, Report 2: Workbook and system user's manual. *Technical Report CERC-89-19.* U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi, 185p.

HALLERMEIER, R.J., 1983. Sand transport limits in coastal structure design. *In:* American Society of Civil Engineers, *Proceedings of Coastal Structures '83,* pp. 703–716.

HANSON, H., 1989. Genesis—A generalized shoreline change numerical model. *Journal of Coastal Research,* 5, 1–27.

HANSON, H. and KRAUS, N.C., 1989. GENESIS: Generalized model for simulating shoreline change. *Technical Report CERC-89-19.* U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi, 185p.

HAYES, M.O., 1967. Hurricanes as geologic agents: Case studies of Hurricane Carla, 1961 and Cindy, 1963. *University of Texas Bureau of Economic Geology Rept. Inv. No. 61,* 56p.

HUBERTZ, J.M.; BROOKS, R.M.; BRANDON, W.A., and TRACY, B.A., 1993. Hindcast wave information for the U.S. Atlantic Coast. *Wave Information Study 30,* U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi, 512p.

KONIKOW, L.F. AND BREDEHOEFT, J.D., 1992. Groundwater models cannot be validated. *Advances in Water Resources,* 15, 75–83.

KOVAR, K., 1990. Calibration and reliability in groundwater modelling. *IAHS Publication 195,* Wallingford, England, 539p.

KRAUS, N.C.; SCHEFFNER, N.W.; HANSON, H.; CHOU, L.W.; CIALONE, M.A.; SMITH, J.M., and HARDY, T.A., 1988. Coastal processes at Sea Bright to Ocean Township, New Jersey. *Miscellaneous Paper CERC-88-12.* U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi, 140p.

LARSON, M. and KRAUS, N.C., 1989. SBEACH: Numerical model for simulating storm-induced beach change. *Technical Report CERC-89-9.* U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi, 256p.

LECKIE, D.A. and KRYSTINIK, L.F., 1989. Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle shelf deposits? *Journal of Sedimentary Petrology,* 5, 862–870.

MCANALLY, W.H., JR., 1989. Lessons from ten years experience in 2d sediment modeling. *In:* WANG, S.S.Y. (ed.), *Sediment Transport Modeling.* New York: American Society of Civil Engineers, pp. 350–355.

MORTON, R.A., 1981. Formation of storm deposits by wind-forced currents in the Gulf of Mexico and the North Sea. *In:* NIO, S.D. (ed.), Holocene marine sedimentation in the North Sea Basin. *International Association of Sedimentary Specialist, Publication No. 5*, pp. 385–396.

NICOLIS, G. and NICOLIS, C., 1991. Nonlinear dynamic systems in the geosciences. *In:* Sedimentary modeling: Computer simulations and methods for improved parameter definition. *Kansas Geological Survey Bulletin 233*, pp. 33–42.

OZASA, H. and BRAMPTON, A.H., 1980. Mathematical modeling of beaches backed by seawalls. *Coastal Engineering*, 4, 47–64.

PEARSON, D.R. and RIGGS, S.R., 1981. Relationship of surface sediments on the lower forebeach and nearshore shelf to beach nourishment at Wrightsville Beach, North Carolina. *Shore and Beach*, 49, 26–31.

PELNARD-CONSIDERE, R., 1956. Essai de theorie de l'evolution des forms de rivage en plage de sable et de galets. *4th Journees de l'Hydraulique, Les Energies de la Mer*, Question III, No. 1, pp. 289–298.

PILKEY, O.H.; YOUNG, R.S.; RIGGS, S.R.; SMITH, A.W.S.; WU, H., and PILKEY, W.D., 1993. The concept of shoreface profile of equilibrium: A critical review. *Journal of Coastal Research*, 9, 255–278.

SIMPSON, D.O.; KADIB, A.L., and KRAUS, N.C., 1991. Sediment budget at Oceanside, California, calculated using a calibrated shoreline change model. *In:* KRAUS, N.C.; GINGERICH, K.J., and KRIEBEL, D.L. (eds.), *Coastal Sediments '91*. New York: American Society of Civil Engineers, pp. 2234-2248.

SNEDDEN, J.W.; NUMMEDAL, D., and AMOS, A.F., 1988. Storm- and fair-weather combined flow on the central Texas continental shelf. *Journal of Sedimentary Petrology*, 58, 580–595.

U.S. ARMY CORPS OF ENGINEERS (USACE), 1984. *Shore Protection Manual*. U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi.

USACE, 1991. *Folly Beach General Design Memorandum*. Charleston, South Carolina, 50p.