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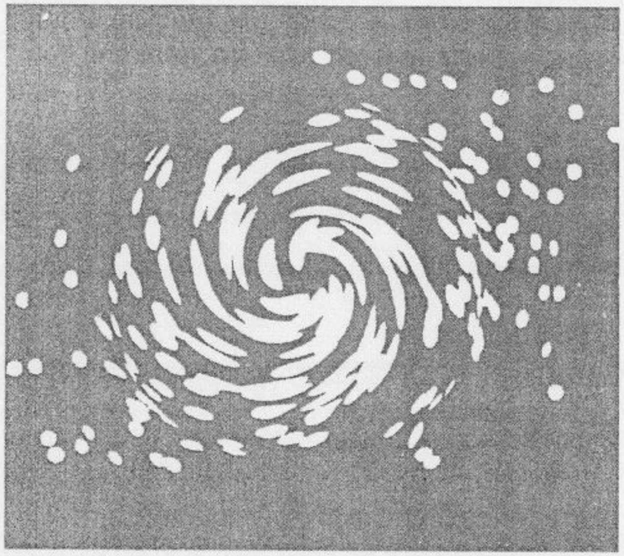
PART THREE

Foreordained Conclusions: Prediction and Politics



Natural hazards happen to us. But sometimes we happen to nature. Beaches are eroding, in part because of our efforts to protect beachfront property. Hard-rock mines release toxic chemicals into groundwater. Nuclear weapons and energy facilities generate long-lived radioactive waste, including some radionuclides that don't exist in nature. When human action is implicated in adverse environmental impacts, it is easy to start pointing fingers. Decisions have to be made. Even a decision to do nothing—to let a beach erode, to let radioactive waste sit around in corroding metal drums—is a decision to do something, a decision that will create winners and losers. On the other hand, a decision to take action, to intervene, is a conscious decision to shape the future. Shaping the future of a beach or a nuclear waste repository is not a simple engineering problem. It is a prediction of how the beach will behave for the next ten years, and how the repository will behave for the next ten millennia.

8

What You Know Can Hurt You: Predicting the Behavior of Nourished Beaches

Orrin H. Pilkey

Over the past century, population pressures, general affluence, the attraction of beautiful coastal beaches, and demands for increased recreation have accelerated the exploitation of our beaches. Meanwhile, diminishing beach sand supplies and rising sea level lead to shoreline retreat. Because beachfront property owners are rarely willing to move their structures farther from the water, human development of shorelines comes into sharp conflict with natural coastal processes. Beach nourishment—adding sand to beaches—has become the favored solution to this conflict, a means of "saving" both beaches and buildings.

As much as 80 percent of the U.S. shoreline is eroding. (The term *erosion*, although a poor descriptor of shoreline retreat, is deeply ingrained in real-world usage and will be used throughout this chapter.) Erosion is caused by many factors, including sea level rise. The *erosion problem*, however, is caused by people who have purchased beachfront property adjacent to a retreating shoreline (see figure 8.1), a relatively small number of people compared to beach users.

The long-term prognosis for the erosion problem is that it will increase in severity because: (1) the number of buildings at risk is growing; (2) beach sand supply—nature's way of nourishing beaches—is being reduced due to channel dredging, damming of rivers, and other engineering activities; and (3) sea level is rising, which increases erosion rates. In other words, the natural sources of beach sand are decreasing, and the natural causes of sand removal are increasing, leading to more net erosion of beaches. Although a number of states have instituted secondary controls on beachfront development (e.g., construction setback lines), no state government has instituted a long-term solution to the erosion problem. Setback lines only postpone the problem to the next generation.

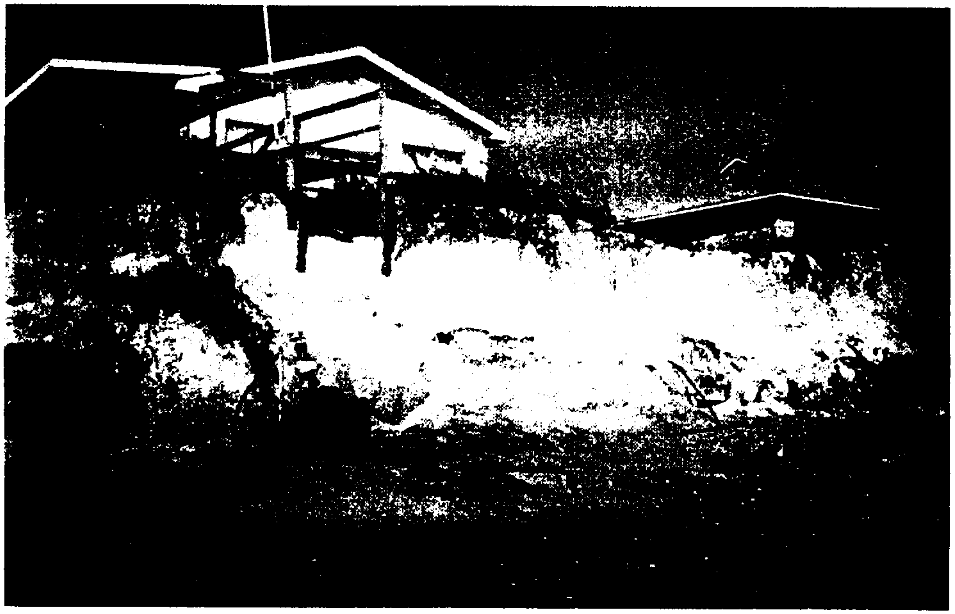


Fig. 8.1 Erosion scarp in a dune on a North Carolina beach. In the foreground are pipes and pavement fragments from a house that was once prime beachfront property.

Responses to shoreline erosion face two societal values that often conflict. The first is the preservation of property adjacent to the shoreline by any means. Beachfront property owners tend to be influential people with the ability and will to defend this value. The second value is preservation of the public recreational beach. The beach is utilized and valued by numbers of people much larger than the numbers of property owners. Conflict arises when, for example, seawalls that destroy beaches are used to protect property.

Our society can "solve" the erosion problem on a developed beach in three ways:

- *hard stabilization*, which is any way of holding the shoreline in place using hard, immovable objects, usually seawalls, groins, or offshore breakwaters;
- *soft stabilization*, or emplacement of new sand, called beach nourishment or beach replenishment; or
- *relocation*, or abandonment of beachfront buildings.

Hard stabilization is the best approach if the dominant societal goal is protection of property adjacent to the shoreline; that is, if preservation of the beach is not considered a priority. Most often hard structures start small and grow in size and length with time. This has been the experience in New Jersey, where shoreline armoring has proceeded for more than a century, leading to a process of total beach degradation now called *New Jerseyization*. Beach loss occurs as the retreating beach backs up against the seawall (or any other fixed object at the back of a beach), gradually narrows, and eventually disappears (see figure 8.2).

If preservation of the recreational beach is the highest priority, relocation is the best approach. Relocation, on a small scale, has been carried out along North American shorelines for decades. This has involved letting an occasional building fall into the ocean, or moving it, as its time comes. Nags Head, North Carolina, loses buildings every year. One cottage, the Outlaw family home, has been moved back five times, a total of six hundred feet, in one hundred years and is currently at the ocean's edge. In recent years, many Nags Head cottages have been replaced by high-rise buildings, a common occurrence on the world's more developed shorelines. The high costs and technical difficulties of moving high-rise buildings reduce the options for a community's erosion response.

Howard and colleagues (1985) argue that retreat, ultimately, is the only option. They conclude: "[Sea] level is rising and the American shoreline is retreating. We face economic and environmental realities that leave us two choices: (1) plan a strategic retreat now or (2) undertake a vastly expensive program of armoring the coast line and, as required, retreating through a series of unpredictable disasters."

Beach nourishment, however, is increasingly the chosen erosion-response alternative, especially on the U.S. East and Gulf Coasts. Some states (South Carolina, North Carolina, Rhode Island, Maine, Texas, and Oregon) have outlawed hard stabilization, making soft stabilization particularly attractive. The United States spends approximately $100 million annually on nourishment (not including the Pacific Coast). Once started, nourishment is a never-ending process. A beach must be repeatedly renourished at intervals—usually between one and ten years—that depend on local wave energy and storm frequency. The new beaches usually lead to intensification of development, providing an ever larger political base for additional funding of future nourishments. Continued nourishment allows the affected communities to ignore the realities of sea level rise and increasing erosion rates as they progressively increase building density and size, which decreases their flexibility to respond to the inexorable dynamics of beach systems.

Most beach nourishment in the United States is carried out by the U.S. Army Corps of Engineers (COE), a federal agency that Congress funds on a project-by-project basis. In order for a federally supported nourishment to be approved, a benefit–cost ratio greater than 1.0 and an

Fig. 8.2 South Myrtle Beach, South Carolina, after the passage of Hurricane Hugo in 1989. The buildings to the left, behind the rock seawall, were partially protected from the storm, but the beach is gone. To the right, the beach retreated, the buildings were flooded by the storm surge, but the beach is wide and healthy. This scene illustrates why society must ultimately choose between beaches and buildings.

environmental impact statement are required (Pilkey and Dixon 1996, p. 10). Both of these requirements are met by predicting the rate of loss of the artificial beach and then predicting the volumes of sand that will be required to maintain a beach of certain dimensions in place for a specified length of time.

The U.S. Army Corps of Engineers Coastal Engineering Research Center (CERC) is the principal organization involved in beach nourishment research. Most of the mathematical models and other concepts used in support of beach nourishment in this country were developed there. The basic procedures used by the Corps are outlined in its *Shore Protection Manual* (USACE 1984).

Predicting the rate of loss of a nourished or natural beach requires an understanding of some very complex surf zone processes. The pace of beach change is extremely rapid, at rates of feet per year, and we have a great number of measurements of eroding beaches. Our direct experience with the phenomenon of shoreline retreat provides at least a coarse check on predictions.

Implicit in the prediction of future beach behavior is the expectation that the sea level will continue to rise. But the mechanics or underlying causes of the current rise in sea level (one foot per century along the U.S. East Coast) are uncertain, as are the mechanics of how a gradual sea level rise causes shoreline erosion. Sea level rise is a much more gradual event than beach changes, which can occur overnight in a big storm. We have not had enough experience with long-term sea level rise to do more than assume it will continue as it has in the past. Thus, in the following discussion of beach behavior, it is assumed that whatever impact sea level rise is having on beach behavior, it will continue at the same rate and in the same fashion for the foreseeable future.

Beaches and Models

Coastal engineers, rather than coastal scientists, produce most of the models used to predict beach behavior. The engineering profession has successfully used mathematical models for many years in the design of engineered structures. Probably in much of engineering, design without modeling would now be considered unsophisticated, even unacceptable. But it is difficult to transfer the mathematical modeling approach from predicting the behavior of steel and concrete structures to predicting the course of earth surface processes.

Models of Beach Behavior

A model represents a system and typically emphasizes those aspects of the system most useful for achieving the purposes for which the model is built. A mathematical model uses equations to represent the system. For example, an engineer could use a mathematical model of a steel bridge to simulate the deflection of a bridge as a truck drives across it: The equations calculate the reactions of the structure as the load is applied. Because the bridge beams and joints are both well characterized and well understood, such a model can be used to design a safe bridge. Modeling the dynamics of a beach to predict its erosion is different, because the dynamics of a beach are chaotic, being subject to random external influences, and because the components of the beach system change as they interact with each other.

The coastal zone is an immensely complex environment, linked to other earth environments in ways that scientists are only beginning to understand. Movement of beach sand and changes in beach shape are initiated by large- and small-scale atmospheric changes (climate and weather) that drive ocean water movement (waves and currents). Organisms constantly modulate the interactions among moving atmosphere, moving water, and moving sediment. They burrow, sort, compact, cement, and extrude sediment, while leaving organic slimes and mats covering the sea floor. These individual complex systems that together constitute the shore—the atmosphere, the bottom sediment, the water column, and the biota—interact in ways that are nonlinear and unpredictable, given our current level of data and understanding. Therefore, any model of a beach must be carefully constructed and tested, and its users must recognize its limitations.

At this point, it is important to emphasize that this discussion is concerned with mathematical models used for applied or engineering purposes as opposed to models used for basic scientific purposes. The distinction is important. The questions that are of direct interest to society when planning beach nourishments involve *where, when,* and *how much*—i.e., predicting where and when we need to put how much sand to nourish a beach. Scientific models may be mostly concerned with *how, why,* and *what if*—i.e., predicting how a beach changes, and why and what if such changes occur. In chapters 1 and 2, Sarewitz and Pielke and Oreskes discussed the distinction between science aimed at predictive precision and science that seeks to deepen insight. The case of beach behavior starkly illustrates the real-world dangers of failing to understand this distinction.

The difference can be illustrated by considering two examples. A mathematical modeling effort concerned with the *how* of beaches is the study of beach cusps by Werner and Fink (1993). In this type of modeling, the number of parameters is held to a minimum: the fewer the better, the simpler the better. Process variables suspected to be key elements of the natural phenomenon are then examined individually. If, under these simple and rudimentary conditions, variation of the parameter produces in the model what has been observed in nature, the parameter is considered to be an important element of the process. On the other hand, engineering models used to plan a beach nourishment must be concerned with the precise future behavior of the beach. To achieve such precision, these models must attempt to include all known significant elements of a process such as the erosion behavior of a particular beach, thus making them much more complex and inclusive.

An early approach to predicting future beach behavior made use of simple, analytical models. Two important examples of such analytical models are the "overfill factor" (USACE 1984) and the "length equation" (Dean 1983).

The *overfill factor* is used to determine the amount of extra sand needed because of the difference in the grain size of the native (original) sand and the fill (nourishment) sand. This model assumes that if the fill sand is finer than the native sand, waves will winnow away the fine fraction of the fill until the native grain size has been achieved. The overfill factor is a simple multiple that determines the amount of extra sand needed to allow for this loss and still have the desired beach. This calculation is implicitly based on the assumption that an equilibrium grain size exists that is determined by the wave "climate," i.e., the average wave conditions over a period of years, of a particular beach. But no such correspondence between beach wave climate and grain size has been recognized. Around the world, beaches with similar wave climate have very different grain sizes depending upon the sources of the sand. Beaches adjust for different grain sizes by changing their shapes and slopes, not only by winnowing away the finegrains.

The *length equation* is used to determine how a nourished beach's length—its longshore dimension—affects its durability. It is based on the assumption that beaches erode at the ends only, and thus the longer a beach, the longer the time required to remove the sand. But years of experience with nourished beaches clearly shows that they do not erode only at their ends. For example, during storms, sand loss often occurs in a direction perpendicular to the shore, and erosion "hot spots" are often not at the ends of nourished beaches.

These analytical models give incorrect results, and users could do simple studies to show they are wrong. Such studies would investigate, respectively, whether fine grains are winnowed away from nourished beaches, and whether nourished beaches of great length systematically last longer than short ones. The observed behavior of beaches shows that these models do not provide accurate nourishment volumes.

Numerical models seek to capture more of the complexity of beach behavior than can be included in an analytical model. Perhaps the two numerical models that have been most commonly used in the United States are GENESIS (see Hanson and Kraus 1989) and SBEACH (see Larson and Kraus 1989), which were developed primarily at the COE Coastal Engineering Research Center by Nicholas Kraus. Both models are user friendly and are available for free on floppy disks from CERC. Both have been used in beach nourishment design. In the following two sections, I describe a key assumption and a key parameter that underlie numerical models to illustrate the empirical challenge of predicting beach behavior. I then review some attributes of the GENESIS model.

The Shoreface Profile of Equilibrium

The most fundamental assumption behind virtually all models of beach behavior is the "shoreface profile of equilibrium." It has been defined as "a long-term profile of the ocean bed produced by a particular wave climate and type of coastal sediment" (Schwartz 1982). The shoreface is usually considered to be the portion of the inner continental shelf across which beach sand is readily exchanged in offshore and onshore directions (figure 8.3). For practical purposes it is the concave upward portion of the inner shelf. On the East Coast, the base of the shoreface, where the much flatter continental shelf begins, is typically ten to twenty meters water depth, but that depth can vary widely. For example, off some barrier islands in the Arctic it is two meters deep, but it extends to a depth of seventy meters on the extreme-wave-energy coast of southeast Iceland.

An important aspect of the concept of equilibrium profile is the closure depth. As used in the mathematical models, it is the depth beyond which seaward sediment transport is insignificant. Closure depth is thus a fence that prevents sediment from moving farther away from shore.

Nourished beach design assumes that the introduced nourishment sand will achieve the "equilibrium profile" once it is sorted out by the waves. Since it is assumed that no sediment is transported beyond the closure depth, the profile ends at that point. In other words, once the equilibrium profile has been achieved, the beach is assumed to be stable. The equilibrium profile is the principal basis for estimating needed sand volumes for nourished beaches. The shallower the closure depth, the less sand required to achieve the correct profile because, as figure 8.4 shows, the beach nourishment sand is assumed to build up the entire shoreface profile to its equilibrium state, and a shallower depth demands less sand. Originally, closure depth was assumed to be at eighteen to twenty meters water depth off east Florida (Bruun 1962). Politics have intervened and closure depth on the east coast of Florida, for purposes of beach design, is now assumed to be four meters, in order to lower the amount of sand putatively needed and thus lower the estimated cost of the beach nourishment, making it politically more feasible.

The shoreface profile is assumed to be described by the following equation relating water depth to distance offshore:

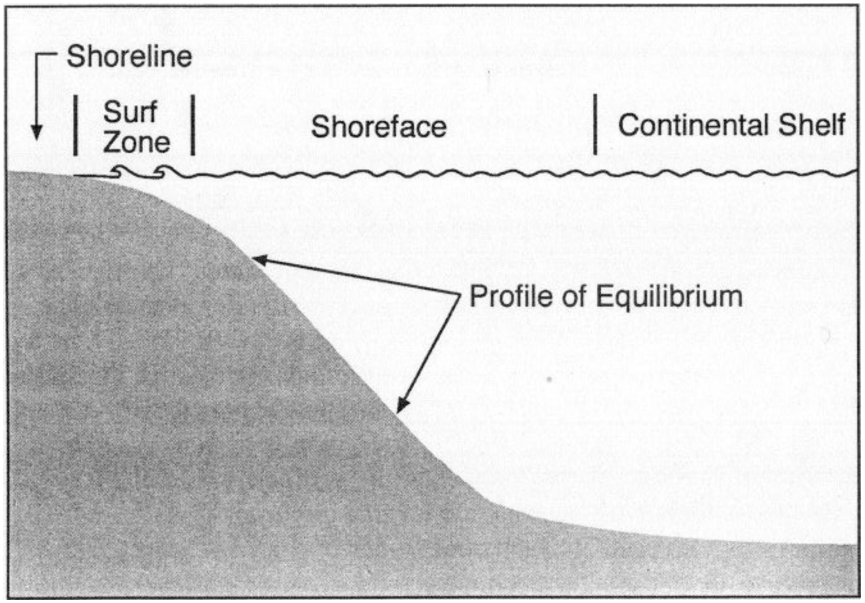


Fig. 8.3 A schematic cross-section of a sandy beach to show some of the terminology used in this chapter. The slope of the shoreface is greatly exaggerated.

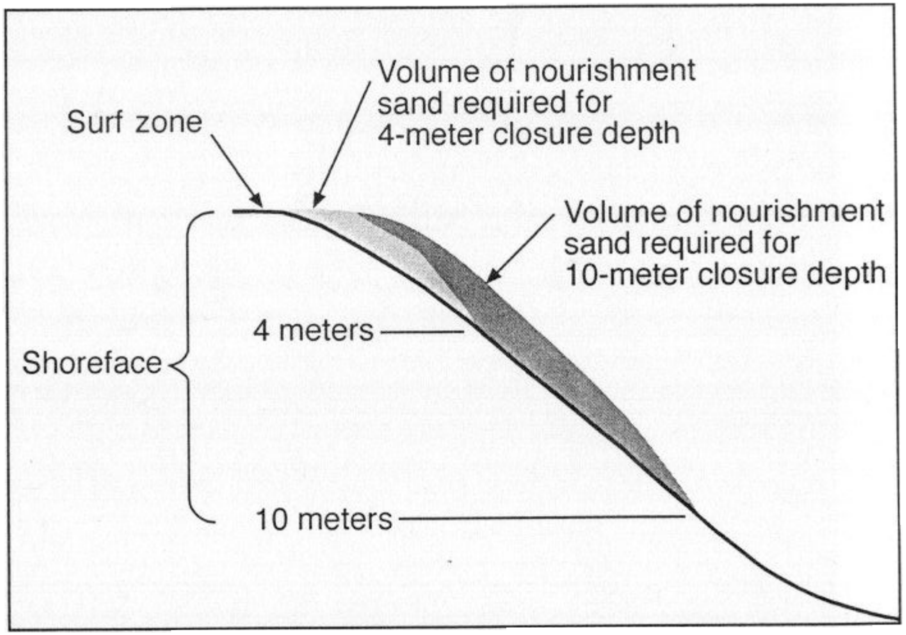


Fig. 8.4 Cross-section of a shoreface showing why the choice of a shallow closure depth results in a smaller volume of sand for a nourished beach. Ordinarily, sand is not pumped onto the shoreface when a beach is nourished. The assumption is made that after the sand is emplaced on the beach, it will be redistributed by wave action, and the beach will eventually achieve the profile of equilibrium. The slope of the shoreface here is greatly exaggerated.

$$h = Ay^n,$$

where h = water depth, y = distance offshore, $n = 0.66$, and A is a factor related to grain size. The equation was derived by measuring and averaging over a large number of real shorefaces (Dean 1977). In the equation, the only parameter representing the character of a particular beach is A, which is assumed to depend only on the grain size of the beach's sand, so that if the grain size of any shoreface anywhere in the world is known, its shape is known. *The problem is that no relationship between grain size and A has been shown to exist* (Pilkey et al. 1993). Furthermore, it is highly likely that wave climate and underlying geology, among other factors, also control shoreface slope.

The concept (as opposed to the equation) of the profile of equilibrium is based on the following oceanographic assumptions:

- ASSUMPTION: ALL SEDIMENT MOVEMENT ON THE SHOREFACE IS DRIVEN BY WAVE ORBITAL ACTION ACTING ON A SANDY SURFACE. Contrary to this assumption, Wright (1995) has shown that on some shores, bottom currents (as distinct from waves) transport large amounts of sediment, yet this transport is not considered in the profile of equilibrium model.

- ASSUMPTION: THERE IS A SEDIMENT-FENCE CLOSURE DEPTH. This assumption is an outgrowth of the idea that all sediment is transported by wave orbital interaction with the sediment. In deeper waters such interaction ceases because the action of waves does not reach bottom, hence the significance of the closure depth. However, there is extensive evidence both in known processes (e.g., bottom currents, the depth of wave action during storms) and observed sediment distribution paths (Thieler et al., 1992) that such a sediment fence cannot exist.

- ASSUMPTION: THE SHOREFACE IS COVERED BY A THICK LAYER OF UNCONSOLIDATED SAND. This assumption means that shoreface heterogeneity plays no role in the model because it is assumed away. However, there is contrary evidence in the literature, i.e., evidence that the geology can play a major role in the evolution of certain beaches. For example, recent studies (Riggs, Cleary, and Snyder 1995) have indicated that in many instances, underlying geology (e.g., outcropping rocks and mud layers) plays a paramount role in shoreface and shoreline evolution.

- ASSUMPTION: OFFSHORE BARS AND OTHER BATHYMETRIC FEATURES DO NOT AFFECT SEDIMENT TRANSPORT OR SHOREFACE BEHAVIOR. This assumption is an outgrowth of the fact that the shoreface profile equation produces a smooth curve without sand bars. But offshore bars in the surf zone are real and are critical factors in surf zone dynamics and sediment transport.

For all of the above reasons, the equation and the concept of the shoreface profile of equilibrium, as used in mathematical models of beach behavior, are wrong. Therefore, any model based on this concept—and most are—has a profound and fundamental weakness.

Modeling Wave Height and Sand Movement

Wave height and direction are the single most important parameters in modeling beach sand transport, because waves are the strongest determinants of beach erosion. Indeed, wave height has been termed the "Rosetta stone" of beach modeling. Wave action at a beach is complex and dynamic. For example, several sets of waves typically impact the beach simultaneously, yet in a model one height and one direction must represent this complicated situation. It is instructive to review how wave height is obtained and used in most models of beach behavior. It is a five-step process, each with significant potential for error.

- STEP 1: PREDICT THE DEEP-WATER WAVE CLIMATE. This is based on wave "hindcasting," i.e., determining a distribution of past wave heights and directions, using published local weather information. Since waves reaching the shoreface can be generated anywhere in an ocean basin and not just locally, the random occurrence of large distant storms is a source of error.

- STEP 2: BRING THE WAVES ASHORE FROM DEEP WATER INTO SHALLOWER WATER. As waves encounter shallow water, their direction changes; a wave refraction model is used to bring waves to the surf zone. Since waves can and often do come from several directions, choosing a single direction is a source of error. Knowing how waves will come ashore requires good knowledge of nearshore bathymetry, but most models mathematically calculate bathymetry using the "profile of equilibrium" equation, which is a source of error. Friction between waves and the sea floor, which varies according to sand grain size and the presence of rock outcrops, is not considered (another source of error).

- STEP 3: CHOOSE A WAVE HEIGHT. Models use a single wave height, and different models make different choices. The model (GENESIS) discussed in the next section uses an average of the highest one-third of waves over a given time interval, while another commonly used model (SBEACH) uses the highest annual wave height averaged over a twelve-hour interval. The former approach considers no storms, and the latter considers only storms. All the waves coming ashore are assumed to be of the same height and frequency and to come from the same direction, completely unlike a natural surf zone, where waves of different sizes may come from several directions at once, an obvious source of error.

- Step 4: Break the waves. The shape of a beach determines how waves will interact with the bottom—how they will break and how they will affect sand transport. Therefore, it is important to know the actual shape of the bottom. Most models assume and use a calculated design beach (from the profile of equilibrium equation) whose shape is determined by sand grain size. This offshore profile is assumed to be constant, while real beaches are dynamic. Sand bars are usually not considered (GENESIS), but when they are (SBEACH), these dynamic features are assumed to be static and unchanging. These assumptions can introduce significant errors.

- Step 5: Move sand. In most models this is done using parameters that relate waves to sand transport and are determined in laboratory "wave tanks" and "sediment flumes" (which are themselves physical models of beaches). GENESIS adjusts the amount of sand calculated to be moved by a factor, K, discussed below. Actual measurements of sand transport in the surf zone are difficult and error-prone (Bodge and Kraus 1991). No comprehensive field information exists to determine the relationship between wave height and transport on a particular beach, or on beaches in general. The lack of information on, and understanding of, real beach sand transport is a source of error.

GENESIS

The Generalized Model for Simulating Shoreline Change (GENESIS) is intended to be used on beaches influenced by engineering structures. As it is now the most widely used model and illustrates well the typical problems with beach behavior modeling, it is emphasized here. GENESIS is designed to simulate the long-term coastal changes resulting from spatial and temporal differences in longshore sediment transport (i.e., movement of sand parallel to the beach) at sites with engineered structures (Hanson and Kraus 1989). The model is used by engineers and planners to predict how a shoreline will move in response to beach nourishment and shoreline armoring or other activities that could alter longshore transport. It is the state-of-the-art model for prediction of shoreline changes (Komar 1998a).

Young et al. (1995) critically review GENESIS and conclude that the model cannot predict beach behavior. Assumptions used in GENESIS, starting with the shoreface profile of equilibrium, either cannot be met or are such simplifications that the model's effectiveness as a predictive tool is limited at best. Frequently, averaged values of parameters are used, smoothing over great potential variability in data sets (waves, grain size, shoreface profile). GENESIS does not consider storms, normally the driving force of beach change. Modelers justify this by saying that using the average of the highest third of waves is adequate to cover the impact of storms, but a single storm (see figure 8.5) can do more than a decade of "normal" weather (Carter and Woodroffe 1994). Moreover, when predictions are made, it is not possible to quantify the error in the predicted results because there is inadequate data to allow useful statistical analysis; in particular, there is typically little preproject monitoring. GENESIS does not provide the modeler with statistical answers.

Fig. 8.5 Storm waves striking the shoreline at South Nags Head, North Carolina. Ordinarily, the greatest changes in beach size and shape occur during storms. In this photo, overwash by waves can be seen entering the town. Onshore loss of sand by this method is not considered in the GENESIS model.

The model consists of two components: a longshore transport equation and a shoreline change equation. The basic physical data required to run the program include:

- current shoreline position (i.e., location on a map);
- wave characteristics (height, period, and direction);
- engineering structures and activities (e.g., the location of groins, jetties, and beach nourishment);
- measured or calculated beach or shoreface profiles oriented perpendicular to the shoreline (i.e., beach geometry); and
- boundary conditions, which can be anything that defines the limits of the beach to be modeled (e.g., a groin or inlet), and estimates of the amount of sand that flows into or out of the beach across this boundary (e.g., due to the permeability of a groin).

All other factors are either physical constants (e.g., the density of water), user-specified constants (e.g., shoreface slope), or calibration parameters (otherwise known as fudge factors).

As the technical manual for GENESIS emphasizes, the user must constantly rely on his or her own technical expertise (Hanson and Kraus 1989). All of the uncertainty discussed above makes GENESIS at best a qualitative rather than a quantitative model and at worst a model that, after a certain amount of adjusting of input parameters, produces a result that the coastal expert expected—a way of backing up one's judgment with what appear to be objective numbers (Young et al. 1995). In spite of these serious shortcomings, many of which are explicitly noted by the inventors of GENESIS (Hanson and Kraus 1989), the model has found wide application.

Have Models Worked?

The long-term costs of beach nourishment have been consistently underestimated, in part because models have not produced reliable predictions of beach life spans and nutrition costs (figures 8.6 and 8.7; Leonard, Clayton, and Pilkey 1990). This underestimation of costs, by itself, is not proof of the failure of mathematical models, however, because politics are involved in cost estimates. That is, the Corps of Engineers, the agency that designs and funds most nourished beaches, is typically under huge political pressure from the Congress to approve proposed projects. Approval is easier to get if the costs are expected to be low. Nevertheless, even leaving out politics, models have failed to make good predictions.

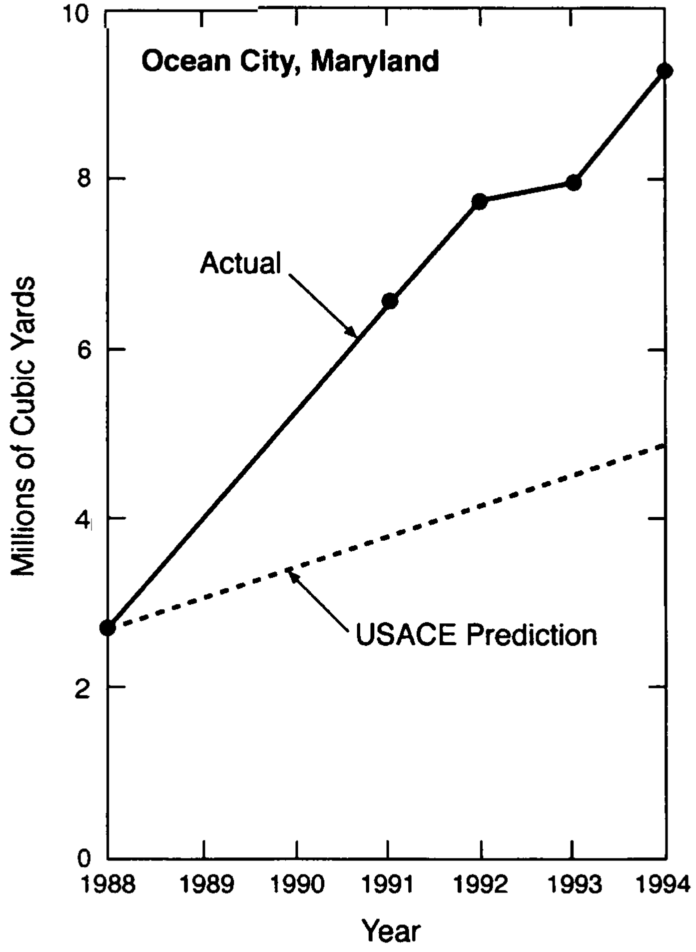


Fig. 8.6 Comparisons of predicted and actual sand volumes required for the Ocean City, Maryland, beach nourishment project. Predicted volume of sand was significantly less than what was actually needed.

One obvious reason for predictive failure is that the design life spans, costs, and sand volumes are given in nonprobabilistic fashion, i.e., as single numbers without error bars. Since nourished beaches are strongly affected by randomly occurring storms, i.e., storms whose magnitude, duration, direction of approach, and frequency cannot be predicted years in advance, large error bars are needed on these numbers. The Corps, however, argues that the Congress and other policy makers cannot understand probabilities and error bars. This argument leads Corps

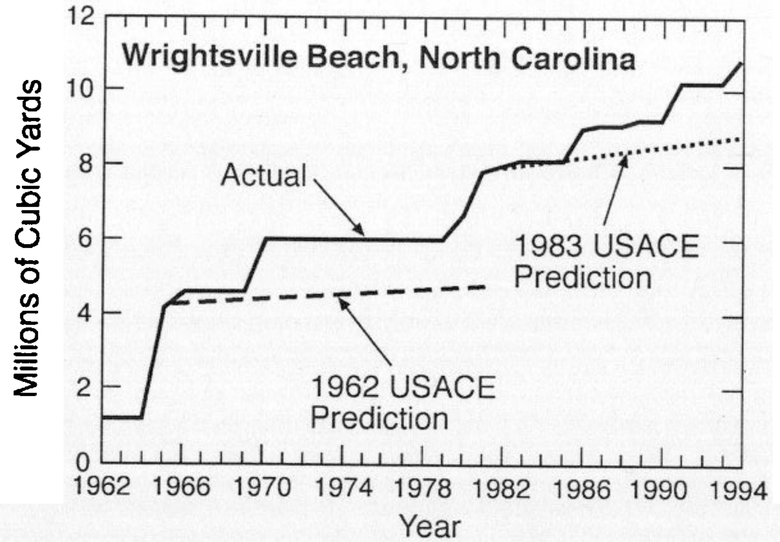


Fig. 8.7 Comparison of predicted and actual sand volumes for Wrightsville Beach, North Carolina, project. Despite fourteen years of experience nourishing this beach, the second sand volume prediction (1982) was still very low in comparison with reality.

scientists and engineers to produce numbers they cannot rigorously defend (Pilkey and Dixon 1996).

Although the failure of beach designers to successfully predict beach life spans seems clear to many, the Corps of Engineers conducted an analysis indicating that their predictive design effort succeeded quite well (USACE 1994; Hillyer and Stakhiv 1997). In short, the Corps argued that predicted costs of nourishment projects were quite similar to the actual costs. The problem with this conclusion, as I have pointed out in the past (Pilkey 1995, 1997), is that the agency did not consider whether a beach stayed in place between renourishments. Often the beach disappeared. One important lesson here is the need for completely independent evaluation of the predictive success of beach nourishment design.

Why Failure Is Not Recognized

For a number of reasons, the lack of success of modeling is apparent neither to the public nor to some scientists and engineers. From the public's standpoint, a time delay of as little as a year seems to be sufficient to let the dust settle from the societal debate over nourishment and

for the details of the issues to fade from memory. The design predictions based on mathematical models become forgotten details in a sea of claims and counterclaims. When a nourished beach disappears too quickly, a number of statements are commonly made in defense of the original prediction. These include:

- The storm was unusual and unexpected. Our society would not routinely accept the "unusual storm" excuse for a failed highway bridge, but it is routinely accepted for the storm-driven loss of artificial beaches.

- The lost sand (from the nourished beach) is just offshore continuing in its function of storm protection. But in East and Gulf Coast beaches, where storm surges may be very large, the principal design element for storm protection (as stated in Corps of Engineer design memoranda for each project) is the berm or artificial dune on the upper beach. Storm protection is the principal justification required for federal funding. Needless to say, the argument that "the sand is just offshore" is very unimpressive to local politicians and chambers of commerce whose principal goal in beach nourishment is to gain a recreational beach and bring back the tourists.

From a technical viewpoint, the problems with model-designed nourished beaches are not recognized by coastal engineers for several reasons.

- *Lack of monitoring.* No nourished beach has been monitored for its design life. Part of the problem is that federal agencies tend to fund monitoring for two to three years, after which it becomes a lower priority and is not funded. Another part of the problem might be a political unwillingness to generate facts that might reveal a low success rate.

- *Lack of monitoring criteria.* Because nourished beaches disappear unevenly in both time and space, declaration of success or failure is complex. Nourished beaches always have erosion hot spots, so it is possible to stand at one location and declare it to be a success. If one kilometer of a three-kilometer beach is lost in a storm, is that a failure? Success or failure should be based on how well the beach is solving the initial perceived problems that led to beach nourishment. The monitoring programs that do exist vary in what is actually measured, so there is no body of agreed-upon standard data or common criteria to compare nourishment efforts.

The Problems with Models

As noted above, the beach is an immensely complex environment linked to other environments, for example, the atmosphere. The beach itself consists of linked components—for example, wind, waves, sediment, and biota—whose behavior and interactions are still not fully understood by the scientific community. This makes modeling challenging but not impossible, depending on one's goals. Models might be used to elucidate principles governing beach behavior; however, *prediction* of specific beach behavior remains very uncertain.

A common modeling objective is prediction of the behavior of a nourished beach for a fifty-year life span. But we are no closer to predicting the fifty-year behavior of a beach than we are to predicting fifty years of weather.

Haff (1996) critically reviewed the sources of uncertainty or error in predictive models of earth surface processes. These include: model imperfections; omission of important processes; lack of knowledge of, and sensitivity to, initial conditions; and external forcing. External forcing—the influence of phenomena outside the beach system—is critically important; for example, randomly occurring storms are not modeled.

Table 8.1 lists some model uncertainties that fall in Haff's categories. *Model imperfections* refers to errors in the characterization of processes inherent in the model itself. One such error is the assumption that parameters in the model are universally applicable to all beaches. A good example of this is the use in GENESIS of sediment transport coefficients, designated by the letter K. The model's longshore transport equation calculates the volume of sand expected to be moved, using two coefficients (or Ks) to obtain an amount of sand transport thought to be "reasonable." This "fudge factor" arose because observed and predicted longshore transport volumes on two California beaches did not match (Komar and Inman 1970). The COE *Shore Protection Manual* (USACE 1984) suggests for general usage K = 0.77, and, as a result, many of the longshore transport volume figures used in the United States are based on this multiple. But why should a single multiple be valid everywhere? Is the longshore transport equation wrong? Or perhaps field measurements of longshore transport are fraught with errors, as demonstrated by Bodge and Kraus (1991). Other field studies have been carried out to determine a better value for K. By comparing observed and predicted longshore transport volumes, values of K ranging from 0.04 to 1.6 have been obtained, representing a span of nearly

TABLE 8.1

Four sources of model uncertainty identified by Haff (1996), as applied to models of beach behavior. Modified from Thieler et al. (2000).

Model Imperfections	Unknown Initial Conditions and Sensitivity to Initial Conditions	External Forcing	Omission of Significant Processes
Assumption of an equilibrium shoreface profile	No (or poor) wave data	Areal and temporal variations in sediment supply	Sediment transport beyond closure depth
Scaling up short-term relationships to long-term (minutes to decades)	No (or poor) historical shoreline retreat data	Multiple, randomly occurring storm events	
Assumption of universal applicability of parameters	Degree of instability of nourished beaches	Storm surge	
		Tidal currents	Water table and/or pore pressure effects on sediment erodibility
Use of adjustable constants as fudge factors	Geology underlying the shoreface		Liquefaction or bed ventilation of surf zone sediments by breaking waves
Use of wave tank data for modeling the prototype			Wave refraction/diffraction effects
	Offshore bars and bedform configuration		
			Storm surge ebb currents
			Wind-driven up/downwelling currents
			Wind-driven longshore currents
			Wave-current interactions

two orders of magnitude in potential longshore transport volumes (Wang, Kraus, and Davis 1998; Stutz and Pilkey 1999). This raises the question: Do we know longshore transport volumes on any beaches?

Perhaps the most important *process omission* in the models is the exclusion of wave-current interactions. The importance of the latter process is that as long as breaking waves suspend sand into the water column in the surf zone, very small currents can transport the sand laterally for long distances. Offshore bars are typically an *unknown initial condition.* Beach behavior may be highly sensitive to such initial conditions, as illustrated by coarse shell lags, the shell pavements found on many beaches and shorefaces that are concentrated when finer materials are winnowed away. If shell or gravel lags exist on a beach, they can delay or alter the response of a beach to storms, resulting in a significantly different storm response than would have occurred in a beach of uniform grain size. Perhaps the most important omission of all in models applied to beach nourishment is some measure of apparent instability of nourished beaches, as indicated by the very high loss rates of artificial beaches relative to their natural predecessors. Rates of loss of artificial beaches can be 1.5 to 12 times those of natural ones, according to Leonard et al. (1990).

Response to Criticism

Criticism of models is usually not well received by modelers; beach model developers and other scientists and users do not engage in a constructive dialogue. Objective oversight is resisted, perhaps because models are involved in determining the allocation of significant funding. It is a sensitive bread-and-butter issue. Critical reviews of models of earth surface processes can be difficult to publish (Haff, personal communication). A common reviewer response is "We are already aware of these problems."

Published criticism of mathematical models of beach behavior has rarely been met with straightforward and balanced critical response in the literature. The bullets below represent typical comments made, both in print and informally, in response to my criticism of mathematical models and their use:

- Models are valuable "as a learning structure for making predictions prior to construction, subsequently monitoring the project, then later comparing predictions with monitoring results . . ." (Houston and Dean 1997).

- We use models primarily to fine-tune results as a check on the various other approaches and tools that we use to design nourished beaches.
- This is the best model we have at our current state of knowledge and until we find something better.
- Simply criticizing the assumptions behind the models is insufficient. It is necessary to run the model and observe its veracity on the basis of actual beach behavior.
- We're learning from our mistakes.
- Model skeptics are "neo-luddites" (Komar 1996).
- Don't throw the baby out with the bathwater.

Impact of Models on Coastal Science

One interesting impact of beach behavior modeling has been the "contamination" of coastal science with concepts originally devised as simplified assumptions for models. Two examples of this are the profile of equilibrium concept and its corollary, closure depth as a sediment fence. Their widespread use in models led to their acceptance, at least in some circles, as valid scientific principles. At present, both concepts, especially closure depth, are widely criticized (e.g., Wright 1995).

In the view of some, the maturity of an earth science specialty can be measured by its success in the use of numerical models for description and prediction of geological processes (Komar 1998b). Such a view holds that the more mathematical a science, the better. The strength of geological sciences, in the view of others, has always been its observational foundation (Baker 1994; chapter 2, this volume).

Ironically, Komar's assertion that coastal geology is a mature science is based on the use of the models critically described in this paper. This view that modeling for prediction is the ultimate in sophistication lends unjustified authority to the modeling approach. Sophistication in predictive modeling is considered so desirable by many scientists and engineers that shortcuts are taken to construct models before the system to be modeled is understood, even though this is actually the opposite of sophistication. Thus, modeling has fostered a climate of carelessness. Assumptions that would never be accepted if examined critically by themselves are tucked into models and never revisited.

Alternatives to Models in Nourished Beach Design

If model-based predictions are unreliable, what alternatives exist? There are three approaches to the design of beaches that do not involve the use of mathematical models (Pilkey et al. 1994):

- *Imitate nature.* This involves studying the beach prior to the nourishment and assuming that the nourished beach will behave like its natural predecessor. Such studies take years. Two examples are the Dutch approach and the Gold Coast, Australia, experience. According to Verhagen (1992), the following process is used by the Dutch to design nourished beaches:

  1. Take beach profile measurements for at least ten years.
  2. Calculate the loss of sand in cubic meters per year.
  3. Multiply this by the desired life span of the nourished beach.
  4. Add 40 percent volume as an "unexpected loss" factor.
  5. Put the sand on the beach.

  Smith and Jackson (1992) discussed the Gold Coast, Australia, approach used on a beach that is very sand rich, relative to those on the U.S. East Coast. More than twenty years of combined wave and profile observations there demonstrated that typhoons cause the formation of large offshore bars that gradually move ashore as part of the storm recovery process. While the bar exists, beach erosion is nonexistent. In two recent nourishment projects, the Australians have constructed an artificial storm bar with nourishment sand (a politically difficult process, since citizens disapprove of pumping sand into the sea rather than onto the beach), and the approach seems to be working by reducing costs.

- *Employ the kamikaze beach approach.* This approach involves placing the sand on the beach with no design effort beyond plans for sand placement and distribution on the beach. This approach to nourishment is funded in the navigation category by the U.S. Army Corps of Engineers. Such nourishment activities are carried out by the COE as an adjunct to navigation projects and do not require their own separate and favorable cost-benefit ratio because they are justified by the improvement in navigation. Beach nourishment in this case is actually a way to dispose of dredge spoil. (The COE must, however, prove that nourishing a beach is the cheapest way to dispose of dredge spoils.) Some of these beaches are very large, including one on Atlantic Beach, North Carolina, of 5 million cubic yards—equivalent to 500,000 dump truck loads.

- *Learn from nearby nourished beaches.* This approach assumes that the nourished beach will behave similarly to other nourished beaches nearby. There are strong regional differences in the durability of nourished beaches on U.S. East Coast barrier islands (Pilkey and Clayton 1989). For example, nourished beaches on the east coast of Florida, south of Cape Canaveral, have typical life spans of seven to nine years. In New Jersey, nourished beach life spans are almost always less than three years. Of course, there are always beaches that don't follow regional trends. That is, despite these regional life-span averages, there are significant intraregional variations. Some are related to occurrences of storms, but, in most cases, the reasons for the variations are not apparent.

  This approach (Pilkey 1988) is essentially a kind of adaptive management—in which decisions are based on recent experience rather than mathematical models—but it remains to be seen whether it will work in the administrative and regulatory framework that governs beach nourishment projects (or whether that framework can be adjusted to be more adaptive).

Conclusions

Mathematical modeling of the behavior of beaches for applied purposes has not been successful in providing reliable predictions to support beach nourishment. Among a number of other things, dependence of beach behavior on randomly occurring storms and a strong sensitivity to initial conditions may doom future efforts to answer *when, where,* and *how much* with sufficient certainty to be an effective decision-making tool. Models currently used to predict beach behavior suffer from the following shortcomings:

- The assumptions behind models are wrong. Assumptions with recognized significant weaknesses (see table 8.1) are routinely used.
- Assumptions aside, adequate data are rarely available for the purposes of setting model initial conditions, determining model parameters, and calibrating the model (including determining uncertainties). (See the list of model limitations from Hanson and Kraus 1989, from the GENESIS manual.)

- The models are gross oversimplifications of complex systems that scientists do not fully understand. Models have not improved apace with our understanding of beach processes (e.g., bottom current studies and recognition of geologic control of erosion), and the assumptions used in the models have thus become increasingly untenable.
- There is a general lack of monitoring, hindsighting, and independent evaluation of model predictions. Not the least of the problems is the widespread acceptance of the "unusual storm" excuse for too rapid beach loss, which precludes objective evaluation of the use of models.
- Adjustment of the model to give generally "reasonable" results or even to match observations in one set of conditions does not imply that the model will give accurate results in other conditions.
- Most models are assumed to have universal applicability on all types of beaches in any wave climate. Clearly, the natural system is too complex for this to be true.

In short, currently used predictive models of beach behavior are inadequate for the engineering tasks for which they were designed. All the same, models remain an important political tool in the ongoing battle over management of our coasts. Despite their proven inadequacies, these models bring scientific credibility—and an aura of certainty—that helps justify the decision to nourish beaches and to continue development of the shore. Thus, an engineering tool has been applied to a scientific problem in order to justify policy decisions that are often controversial. Nature, however, pays no attention, and shorelines continue to retreat.

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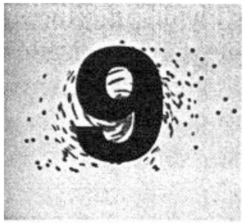

Is This Number to Your Liking? Water Quality Predictions in Mining Impact Studies

Robert E. Moran

If one is to mine gold commercially in the western United States, the operation is likely to be at least partly on federally managed land—most often managed by the U.S. Bureau of Land Management (BLM) or the U.S. Forest Service. Such federal lands constitute about 50 percent of the eleven western states and 90 percent of Alaska. Portions of mines may also be on private lands. Most such operations are huge open-pit mines, sometimes more than a thousand feet deep, nearly a mile wide, and more than a mile in length. The land management agencies oversee the issuing of permits as well as subsequent operations with the intent of minimizing future impacts to the site and its resources. However, the construction of such huge pits inevitably involves moving and exposing massive volumes of rock, often hundreds of feet below the water table. Once mining ceases and the dewatering pumps are shut off, a lake will form within the excavated pit up to the level of the water table. Because pits of this scale were first constructed at gold sites only in the late 1980s, we have no appropriately long-term information on the chemistry of the resultant pit waters; many of these pits are still being excavated, and the pit lakes have yet to form.

Mining regulatory agencies like the BLM face a dilemma when issuing permits for such mining activities. On the one hand, they are required to prepare environmental documents that should disclose any anticipated significant damages to the resources of the site and describe appropriate mitigation procedures. On the other hand, they are mandated by agency policy, and apparently by legislation as well, to promote mining activities on federal lands. My discussions with numerous BLM staff in Idaho, Nevada, Utah, Montana, and Colorado have confirmed that their operations are strongly guided by the mandate to promote