How could there be so much pretense, so much delusion, so much auto suggestion; why play such laughable games?

—*Vaclav Smil, University of Manitoba professor and author of* Energy at the Crossroads, *in reference to quantitative mathematical models used to forecast energy trends*

chapter nine

a promise unfulfilled

The Haff Principles

In the preceding chapters, a number of modes of mathematical model failure have been recognized, the sum total of which points to the virtual impossibility of accurate quantitative modeling to predict the outcome of natural processes on the earth's surface. Physicist-turned-geologist Peter Haff has categorized the fatal flaws in such models, most of which we have at least briefly touched on earlier in this volume. Haff specializes in the study of desert pavement, the rocky surfaces that form upon long exposure of the desert surface to sun, wind, and alternating freezing and searing temperatures. He has long perceived the futility of quantitative mathematical modeling of natural processes even as he studies the evolution of desert landscapes with qualitative mathematical models. The four most salient problems are the following:

- errors in characterization of the processes being modeled
- omission of important processes

- lack of knowledge of initial conditions
- intrusion of forces that influence events from outside the system

One of the most common sources of quantitative modeling error is *inaccurate characterization of the processes being modeled.* For example, averaging parameters in modeling is always necessary to reduce the size of the databases. Hence numbers used to describe environmental conditions, whether they be wave heights, water and atmospheric temperatures, sand grain size, groundwater flow rates, or fish abundance (among many others), are of necessity expressed as *averages.* But averages are a wooden, clumsy way to characterize nature. Nature herself doesn't deal in averages.

The late Stephen J. Gould, Harvard paleontologist extraordinaire, author, and baseball fanatic, argued in his book *Full House* that *reification* is the big danger that arises from averaging. According to Gould, the term was coined by philosophers and social scientists in the mid-nineteenth century and "refers to the mental conversion of a person or abstract concept into a thing. . . . We abstract the variation within a system into some measure of central tendency like the mean value and then make the mistake of reifying this abstraction and interpreting the mean as a concrete thing." In other words, we forget that the mean value of some natural trait is just that, the mean or the average—a value that may never actually occur on the ground.

Scaling up occurs when short-term observations or predictions are scaled up to make long-term predictions. The mother of all scale-ups is, of course, the modeling effort at Yucca Mountain. A database involving, at best, decades of observations is used to predict radioactive waste behavior a million years into the future.

Substituting laboratory measurements for nature is often necessary because observing the same relationships in nature is complicated by too much statistical noise, not to mention the time, expense, and difficulty of getting measurements in extreme events. But the lab is never as good as the real thing. Substitutes for the natural world include wave tanks and flumes to imitate surf zones and rivers, wind tunnels to study sand transport, greenhouses to observe plant response to climate, and aquariums to study aspects of fish development.

Substituting mathematics for nature can be even shakier than using lab measurements. The Army Corps of Engineers explained that it used a mathematically derived offshore profile shape (equations 4 and

5, appendix) to put into the model GENESIS because natural profiles on the North Carolina Outer Banks, of which many measurements were available, were too variable!

Another common problem, one that is very difficult to address in quantitative models, is the assumption of *linearity* or *nonlinearity*. In most modeling of complex systems, the relationship between parameters is assumed to be linear. The relationship between parameters forms a straight line on a graph, making it easy to perceive, easy to work with. In reality, simultaneous relationships between multiple parameters in models—for example the relationship between wave-formed currents and sand transport on beaches—are very complex and usually nonlinear. Such relationships do not plot as a straight line and become difficult, if not impossible, to handle in models.

It is an axiom of mathematical modeling of natural processes that only a fraction of the various events, large and small, that constitute the process are actually expressed in the equations. Note the list of factors that affect shoreline retreat rates in chapter 4 and the list of parameters responsible for sand transport on beaches in chapter 6. The hope, of course, is that the omitted processes matter little. Unfortunately, *omission of important processes* is commonplace. The failed model predictions attributed to so-called unusual events, such as an unusual storm, an abnormal flood, an unexpected wind, an extraordinary rainfall, unanticipated temperatures, or atypical water compositions, are often caused by an omitted process, which was incorrectly assumed to be unimportant. For example, the role of bacteria in chemical reactions in abandoned open-pit mine lakes is commonly omitted, as is the role of wind in determining the velocity of the surf zone currents that carry sand. The common "unusual event" excuses for failed modeled predictions, more often than not, are actually omitted processes.

The processes that transport sand on the seafloor near the shoreline provide a good comparison of the difference between the world of modeling and the real world. If you had just arrived on a spaceship from Mars and found yourself examining the world of coastal science, you could be forgiven for thinking that there must be two oceans. One is the ocean as envisioned by those who mathematically model it; the other is the real ocean. The number of factors in the real ocean that affect seafloor changes and sand transport is large, and the number of permutations and combinations of these factors is vast. The modeler's ocean, however, is slightly more complicated than a tub of water, with waves that are of perfectly uniform size, all coming from the same direction over

a smooth, featureless seafloor covered by a blanket of perfectly uniform sand grains.

Initial conditions must be well known before an earth process or an earth system is modeled. *Lack of knowledge of initial conditions* can "effectively prohibit detailed prediction of system evolution," according to Haff. Dependence upon initial conditions is an important characteristic of chaotic behavior, as illustrated by the classic experiments of MIT professor Edward Lorenz in the early 1960s. Lorenz's famous butterfly effect, employed in every textbook about chaos, is about initial conditions. The story goes something like this: a butterfly flaps its wings in the Amazon, creating a very minor atmospheric disturbance that leads eventually, through many steps, to a tornado in Texas.

As explained by James Gleick in his book *Chaos*, "Tiny differences in input could quickly become overwhelming differences in output"—a phenomenon he describes as "sensitive dependence on initial conditions."

Gleick relies on folklore to provide an example of extreme sensitivity to initial conditions:

> For want of a nail, the shoe was lost
> For want of a shoe, the horse was lost
> For want of a horse, the rider was lost
> For want of a rider, the battle was lost
> For want of a battle, the kingdom was lost
> And all for the want of a horseshoe nail.

External forcing (forces intruding from the outside) occurs in so-called open systems where, according to Haff, "mass, energy and momentum can enter and be discharged through the system boundaries." He also notes that characterization of external forcing becomes an increasing problem for modeling as the size of the natural system increases. The most important form of external forcing in beach modeling is randomly occurring storms that pass right through or close enough to the shoreline in question to produce waves.

Storms are external forcing elements for invasive plant pests as well. Hurricanes frequently blow in new species (such as soybean rust, which may have arrived with Hurricane Floyd in 1999). Ocean currents are external forces for fishery modeling. Groundwater flow from outlying areas is an external forcing element for both Yucca Mountain and water quality quantitative modeling in general.

To Haff's list of model problems we would add ordering complexity, the problem we have discussed in most of the chapters. Even if all the parameters are thoroughly understood, the order and magnitude of their participation in the process remains unknown.

A Tainted Era

Among the early model skeptics, J. H. Chessire and A. J. Surrey in 1971 noted that because of the mathematical power of the computer, the predictions of computer models tended to become "imbued with a spurious accuracy transcending the assumptions on which they are based. Even if the modeler is aware of the limitations of the model and does not have a messianic faith in its predictions, the layman and the policymakers are usually incapable of challenging the computer predictions. . . . A dangerous situation may arise in which computation becomes a substitute for understanding a complex system." This, at a time when models were revered, sacrosanct, and seldom criticized.

If prediction by models is an albatross around the neck of those concerned with earth processes, it may be even more so for economists and others who model human behavior. Stock market trends and energy futures are as complex as natural processes, with the added complication of human behavior. William Sherden in his book *The Fortune Sellers* says, "So long as we do not question the validity of forecasts and think for ourselves, we will be destined to be deluged by a constant reign of error from those dismal scientists [economists] ever eager to fill our need for prediction."

In this volume we have viewed at least two dozen different kinds of quantitative model efforts, seven in particular detail. Most of these efforts to predict the outcome of complex natural and human related processes involve using several models in tandem. At Yucca Mountain, the modeling effort combines hundreds of models. We believe there are none that can predict accurately the outcome of complex natural processes, but there are degrees of differences in the recognition of model weakness among those that do the modeling.

Table 9.1 is a purely subjective ranking of the flavor of quantitative modeling effort in various science and engineering specialties. This is not a ranking of predictive modeling capabilities, since in all of these cases we believe actual accurate predictions are not a possibility, now or in the future. Instead, the ranking is based on the degree to which uncertainties are recognized and publicized by the particular modeling community, the vigor of the debate about model validity in the technical literature, and the usefulness of the modeling effort, not in predictive successes but in advancing our knowledge of natural processes.

Table 9.1 Ranking of the Flavor of Quantitative Modeling Efforts in Various Science and Engineering Specialties

Beach Nourishment Life Spans	WORST
Bruun Shoreline Erosion Rates	↓
Abandoned Mine Pit Water Quality	↓
Yucca Mountain Nuclear Repository	↓
Allowable Fish Catch	↓
Global Sea-Level Change	↓
Invasive Plants	BEST

Each of the modeling groups or specialties has its own distinctive personality. The modeling of beaches for coastal engineering takes the cake as the worst of the bunch. There is not the slightest public recognition of problems with the models, and the models are so tightly bound up with politics that the answers are essentially useless, except to those whose purposes are served by inaccurate answers. Fudge factors are routinely used, looking back to learn from the past is simply not done, and most practitioners remain blissfully unaware of, or at least uncaring about, model weaknesses. The problem is amplified because engineers who use the models are rarely specialists in sedimentary geology, and they fail to appreciate the model's detachment from reality.

Engineering models for highways, buildings, and elevated water tanks usually afford some opportunity for correction, and unanticipated problems can be corrected during construction or initial testing. Such options don't exist for models of natural processes, however. Naomi Oreskes notes that "modern aeronautical designs are developed on computers [models] but no one ever buys a ticket on a commercial jet before a prototype has been flown for many hours." The problem is that engineers often don't recognize the difference between the behavior of natural processes and the behavior of steel and concrete.

Artificial beach life spans, shoreline erosion rates, and abandoned pit lake composition modeling are generally not adding significantly to our understanding of natural processes. The modeling efforts in these three fields follow separate and independent paths from current field investigations. The other modeling efforts listed in the table have spawned detailed studies that have contributed immensely to the science. Even if ordering complexity prevents accurate prediction of the future in these fields, the increase in knowledge of the causes of global change, fishery science, invasive plants, and the evolution of waste stored at Yucca Mountain will serve to provide a strong basis for qualitative estimates or risk analyses. The advance in knowledge of groundwater transport through rocks above the groundwater table (the vadose zone) has been a particularly fruitful aspect of the Yucca Mountain studies.

Agency incompetence and intransigence such as that exhibited by the Bureau of Land Management or the Army Corps of Engineers add another element to the spreading use of models. Without the models that provide favorable cost-benefit ratios and positive environmental impact statements, the agencies would be virtually out of business. In part this situation has been caused by the U.S. Congress, which requires some government entities, especially the Corps of Engineers, to sing for their supper. No projects—no budgets—no agency—no jobs. Under such circumstances it is no wonder that nonworking mathematical models are accepted unflinchingly if they will lead to project approval.

Policy scientist Ron Brunner thinks that part of the problem of model overemphasis is scientific hubris—if Newton and Einstein could do it, so can we. He thinks another driving force is the *law of the hammer.* To a small boy with a hammer, everything looks like a nail. To a scientist schooled in modeling, mathematical models answer all questions. Victor Baker, former president of the Geological Society of America, says, "Allowing the public to believe that a problem can be resolved . . . through elegantly formulated . . . models is the moral equivalent of a lie."

Totally consumed by the belief that to be quantitative is to be in the forefront of science, modelers consider nonbelievers to be neo-Luddites. Responses to criticisms and excuses for failed predictions follow several predictable lines, such as the following:

- The storm (flood, sea level rise, pit lake composition) was entirely unexpected due to very unusual conditions.
- We're learning from our mistakes.
- This is the best model we have at our current state of knowledge and until we find something better, don't throw the baby out with the bathwater.
- Models aren't all that important—we just use them to fine-tune results and as a check on other approaches and tools we use.
- Simply criticizing the assumptions behind the models is not enough. It is necessary to run the model and check it out.

Often modelers will note weak assumptions and sources of error in the technical literature but then pass right on by and present their model and recommend its application elsewhere. It's as though a difficulty can be overcome by recognizing that it exists. So it went with the Army Corps of Engineers technical manual on the SBEACH model. A tabulation of virtually devastating problems and uncertainties is scattered throughout the manual for model users, but in the end the model is recommended for use. As mentioned earlier, use of the model for nourished beach design is even required by law in Florida. Passing by weak assumptions is what Ron Brunner refers to as "uncertainty absorption."

Two more critical aspects of quantitative modeling remain to be mentioned. These are hindcasting and the demarcation problem otherwise known as the white swan problem.

Hindcasting is not forecasting, but it is widely accepted that reproducing the past is the same as a successful prediction of the future. This is one of the most common and misleading missteps of modern quantitative mathematical modeling, especially among academic scientists. For example, because a model successfully "predicts" past climate changes the assumption is made that it will predict future changes. Although this belief has been challenged a number of times (e.g., Naomi Oreskes), it still persists. But it is clear that in complex natural systems, successful prediction of one event doesn't mean that it will work the next time the model is applied.

Demarcation is the term used by science philosophers to describe the problem of distinguishing bad science from good science. Sir Karl Popper, an Austrian-born British philosopher of science, argued that a valid scientific theory must be based on falsifiability. He illustrated this by his famous tale of an individual who, convinced that all swans were white, looks only for white swans to verify his belief. Popper's point is that the person ought to be searching for black swans, since a single black swan would mean his intuition was wrong. So it is with models. Scientific mathematical modeling should involve constant efforts to falsify the model. To do otherwise is invalid science. It is easy to find evidence to support a model, a theory, or one's intuition by looking only for the "white swans." For example, the Bruun Rule model for predicting shoreline erosion rates was validated by finding a few locations where it seemed to work (the white swans) while ignoring many other locations where it didn't (the black swans). Opponents of the reality of future sea-level rise who are motivated by economics are constantly looking for white swans. Of course, the white swan problem affects all of science, as well as other segments of society, such as those who predict trends in stock market prices. But the impervious nature of the inner workings of models makes them particularly vulnerable to selective calibration or concentration on finding only white swans.

The Damage Done

That applied quantitative modeling has been damaging to our society is obvious. We have provided numerous examples of this in the previous chapters. Whether directly the result of using models to avoid data gathering, the politicization of models, the use of models as fig leaves, or the use of models by those who have no idea what they really are, the results are the same. Society is misled. Society loses.

A common justification for modeling is that it allows understanding of processes that are difficult or very costly to study in the field, such as the processes in a surf zone. With increasing frequency, however, much-needed field and laboratory studies are a casualty of modeling. Modeling offers a handy excuse to avoid investing in a lengthy and costly field study; why do so when one can just sit down at a computer and solve the problem?

Another victim of modeling can be robust science. It is the nature of scientists to be questioning and skeptical, a treasured tradition that has resulted in legendary societal debates on issues ranging from the origin of the universe to the evolution of life to the causes of disease. Our experience indicates that studies that are critical of quantitative models are most often completely ignored. In the technical literature, with the occasional exception of climate change modeling, the modelers circle the wagons to form a protective shield around their numbers. They are not unlike religious fanatics. Applied mathematical modeling has become a science that has advanced without the usual broad-based, vigorous debate, criticism, and constant attempts at falsification that characterize good science.

The widespread use of model simplification goes against the grain of good science even though it is a perfectly valid basis for qualitative modeling. A model simplification is an assumption or concept that is generally wrong but is believed to be close enough to reality to be used to make its application much simpler. Assuming, for example, that the highest one-third of all waves is a good measure of wave height has become a widely used simplification in equations used to calculate beach sand transport. But in a number of modeling communities, simplifications have drifted

into scientific principles. For example, the study of beach sand transport has brought the concept of a shoreface profile of equilibrium related only to grain size and the offshore sediment fence known as the closure depth into mainstream science. The problem is that neither of those things exists in the real world.

Robust science is also damaged in the publishing process. The concept of the various categories of model uncertainties formulated by Peter Haff and discussed above is from a technical article in a rather obscure publication. It is a major contribution to the understanding of model weaknesses, but it was flatly turned down by the first (and much more prestigious) journal he submitted it to. Basically the editor and reviewers said that there was nothing new here; the uncertainties were well known by modelers. Policy scientist Ron Brunner had the same experience with a paper that was critical of global change modeling. He was informed that his paper was beating a dead horse—exactly the criticism that Haff's paper received. Brunner eventually published his paper, after three rounds of reviews. He accomplished this by carefully documenting that although modelers may have recognized the weaknesses as they had claimed, they had failed to mention this in the technical literature or in any public setting.

The integrity of science is an issue as well, especially in politically sensitive modeling. Unjustified claims of modeling successes abound. A frequent claim is that past model applications have been monitored to determine success or failure and to improve the models. This, however, is rarely the case when it comes to earth surface process modeling. Even if monitoring is done, true believers are never the best judges of their accomplishments and tend to monitor through rose-colored glasses. Claims of looking back or monitoring the results of modeling must be looked at very carefully and skeptically. It is critical to lift up the flap of the tent and take a close look at the underpinnings of such claims.

James Wilson, the University of Maine fishery economist, sums up his academician view of mathematical models in U.S. fisheries as follows:

> The models are not verifiable and no attempt is made to verify. The result is that we don't learn, except at an extremely slow rate. Almost all the science is done in government facilities and what's not done in government facilities is done on government contract. There is no independent body capable of giving depth and breadth to an alternative view. Academic scientists, including ecologists, often get involved but find that the National Marine

> Fisheries Service becomes an attack machine when there is any substantive disagreement. In short, the institutions that keep science vibrant and progressive are absent.

And society suffers accordingly.

Societal damage from applied models can be extreme. After World War II, the RAND Corporation took over operational research for the U.S. Air Force and quickly changed its nature. It soon became systems analysis, which addressed the problem of what new equipment and tactics were needed to accomplish the mission of holding the Soviet Union at bay. During the war, operational research had examined existing tactics using existing equipment. Systems analysis, on the other hand, dealt with unknowns in the nearly complete absence of data. Operational research was concerned with military experience and was based on hard facts.

The RAND Corporation's quantitative model studies were behind many of the cold war decisions that eventually cost and perhaps wasted billions of dollars. Model-backed decisions included the Strategic Air Command's choice to build intercontinental bombers, as well as the decision to substantially increase the size of our nuclear stockpile. Among other things, RAND perceived a missile gap with the Soviet Union when our missiles were far better and much more numerous. Secretary of Defense Robert McNamara approved construction of hundreds of Minuteman missiles, bulldozing intelligence estimates and common sense, all the while shielded by the fig leaf of the RAND quantitative mathematical models.

Paul Edwards, in his 1995 book on computers and the cold war, argues that enormous military investments were based primarily on mathematical models that used assumptions that were based on the ideas and opinions of the civilian analysts at RAND. "The appearance of hard answers achieved by extensive quantitative analysis and simulation lent an air of certainty to results even when based on uncertain assumptions, especially at a moment in American history when the prestige of science and technology had reached an all time peak." In the end, the models just expressed some opinions.

A Qualitative World

Whatever alternatives society chooses to replace quantitative models, it will first be necessary to make fundamental changes in our approach to designing with nature. Accurate estimates of the outcome of natural

processes must not be expected or required. Cost-benefit ratios must become a thing of the past, because determination of both costs and benefits requires accurate quantitative models. Accurate environmental impact predictions are impossible as well and should be considered ballpark figures. Accurate predictions of future climates, sea-level changes, shoreline erosion rates, and fish populations should be recognized as impossibilities. We will simply have to move into a more qualitative world.

In many ways we are already there. William Gray, the hurricane guru of Colorado State University, predicted in December 2004 that the 2005 hurricane frequency would be above average (six hurricanes and eleven named storms) but not as bad as the 2004 season. In the year of Katrina, all bets were off, all predictions were wrong, and the naming of storms used up A through Z and dipped into the Greek alphabet.

The much-respected Gray utilizes a purely qualitative modeling approach, hindcasting the relationship between past atmospheric conditions and hurricane activity. Previously he used the rainfall pattern in West Africa, but for reasons that are not clear, after 1995 this approach seemed to fail. The new approach uses six atmospheric predictors that seem to be related to hurricane activity. His is a *statistical model* that does not require an understanding of why a relationship exists—only acknowledgment *that* it exists. Gray says that the method is valid "provided the atmosphere continues to behave in the future as it has in the past. We have no reason for thinking that it will not."

To reiterate, qualitative models are those that answer what if, how, and why questions as opposed to the where, when, and how much questions that quantitative models tackle. Quantitative models are expected to produce answers accurate enough to be useful for a wide range of societal purposes. Qualitative models are supposed to predict directions, orders of magnitudes, and the mechanisms behind natural processes.

"What if " qualitative modelers suppose that an event of some kind will occur and then evaluate what the consequences might be. As part of their study of the ongoing drought in Arizona, for example, geologists and hydrologists are concerned with understanding the dropping level of Lake Powell behind Glen Canyon Dam. The lake level has dropped 137 feet since 1999.The worst known drought in the area, examined through tree ring studies, occurred in the 1500s and lasted for thirty-eight years. Hydrologist Ron Harding asked the question What if we assume a drought that is drier but lasts as long as the sixteenth-century drought? This was a what-if worst-case scenario. Harding modeled the hypothetical plummeting lake level, with the startling result that the lake level now is plummeting faster than it does in the modeled, worst-case natural scenario. The reason, of course, is the heavy use of Colorado River water by Nevada, Arizona, and California, superimposed on the lake water lowering caused by the drought. This what-if qualitative modeling pointed out the gravity of the lake level drop.

The dikes that failed in Hurricane Katrina around New Orleans provide a tragic what-if qualitative modeling case in point (figure 9.1). Louisiana State University modelers predicted years ago that the Mississippi River Gulf Outlet (MRGO) canal would accentuate storm surges and endanger New Orleans. The model-based warning was ignored, and sure enough, the canal raised the storm surge at the head of the canal, causing a dike failure at that point.

An excellent example of a qualitative model used to answer a "how" question involves a study of the origin of tors, which are rock pillars or crags a few tens of meters high on the surface of pediments. Pediments are broad aprons at the base of many mountain ranges in the arid southwestern United States, for example, the Wonderland of Rock in Joshua Tree National Park. They are large flat erosion surfaces, covered by thin layers of sand and gravel.

Why and how tors form has been the source of much discussion among geologists. Current theories mostly center on the idea that there are variations in the underlying rock types, and the fact that some weather faster than others may explain why the rock knobs are present. That is, the tors would be the most resistant rock. Alternatively, some argue that fractures and faults may cause localized accelerated weathering, thus isolating adjacent highs where weathering is slower.

However, many tors form on pediments where both the frequency of fractures and the rock types are essentially uniform, so the prevailing theories can't always explain them. Mark Strudley, a modeler and graduate student, theorized that tors might form because unconsolidated sediment surfaces (and the underlying rock) are gradually lowered at a faster rate than bare rock alone. Such rates of lowering are in the range of tens of meters per million years. By this hypothesis, the tors form where conditions favor a very thin to nonexistent sediment cover. Strudley modeled pediments and the processes of evolution on its surface. The model produced a tor shape and an areal distribution of tors (on paper) that was similar to actual tor distribution (figure 9.2).

It would have been possible to theorize the relationship between sediment thickness and tor evolution (especially with extensive fieldwork) without the model, but the use of the qualitative model provided

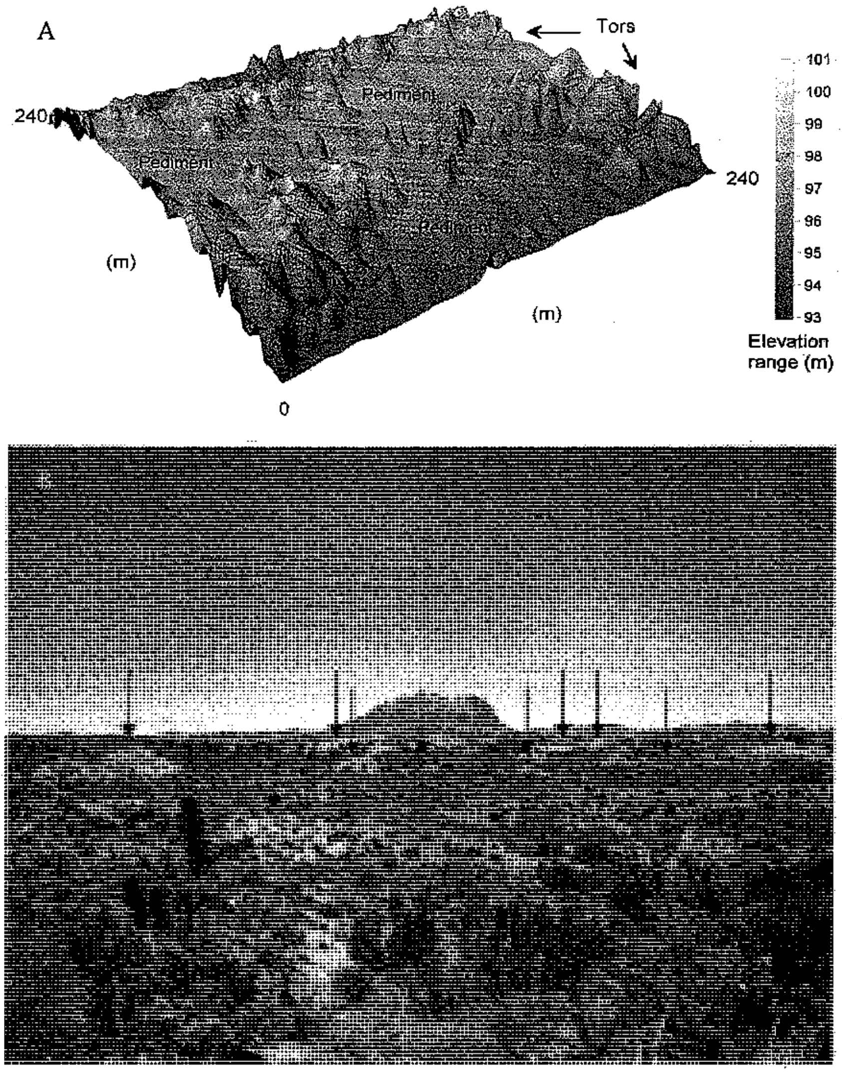

Figure 9.1 An example of the use of a qualitative mathematical model. Here the question was how do tors, the rocky crags that protrude from the desert surface, form? Modeler Mark Strudley assumed that tors forms where relatively thick sediment covers retarded weathering, allowing adjacent surfaces with thinner sediment cover to lower more quickly. The resulting modeled image of the desert surface (A) is remarkably like the real thing (B). This shows that Strudley's proposed mode of formation of tors is feasible, but it does not prove that this is the mechanism that is actually in play. Photos courtesy of Mark Strudley.

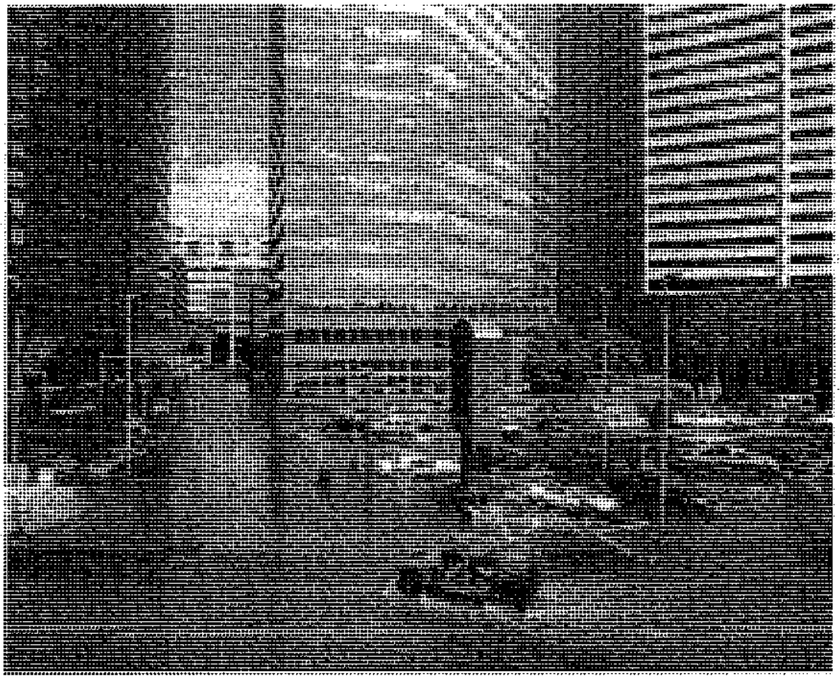

Figure 9.2 The flooding caused by Hurricane Katrina could hardly be considered unexpected. This photo from the downtown area of New Orleans shows relatively shallow but still very damaging flooding. Qualitative modeling showed long ago that the flooding was likely when the "right" storm from the "right" direction came by. One model correctly predicted that the Mississippi River Gulf Outlet (MRGO) navigation channel leading from the city to the open Gulf of Mexico would act like a funnel and enhance the level of the storm surge, causing the water to overtop the dikes. Photo courtesy of the U.S. Army.

strong support for the idea. In addition, the computer model allowed examination of surface behavior that would not have been possible to derive with simple reasoning of the human mind. The fact that the model reproduced reality, however, is not absolute proof that this mechanism is responsible for tor formation. Also, of course, the other mechanisms theorized by earlier workers may well be operable at the same time.

Probably the main opposition to casting aside the quantitative approach to prediction of the path of natural processes will be the engineering community, for they are the ones who brought mathematical modeling out of the world of concrete, asphalt, and steel, where the laws of physics prevail, into the chaos and complexity of the physical and biological processes that work on the earth's surface. Quantitative engineering

modeling is a very successful component of modern engineering practice. Engineers excel at predicting the impact of natural processes on human-made structures, such as the effects of wind on a building. That is a different problem from predicting the outcome of natural processes such as storm winds on a beach or the eventual composition of the lake in an abandoned open-pit mine.

In our personal interactions with engineers we have learned that change may not come easily. A few years back we presented a paper arguing that the model GENESIS, which predicted the evolution of artificial beaches, could not possibly work. Afterward an engineer came up and expressed outrage concerning our study. After listening to her tirade for a while, it became clear that she was not questioning the veracity of our findings. She was offended that we had dared to question such an important model.

In a recent question-and-answer session, again concerning beach models, an engineer from the U.S. Army Corps of Engineers responded to criticisms by using all the standard answers, such as the assertion that the models had been calibrated and verified and there were no problems with using average grain size and average wave height. When it was pointed out that his model did not consider storms, he noted that his organization was in the process of correcting that. Although he was basically wrong on all counts, what soon became clear was that he was as certain of the model's validity as he would be of the formulas used to determine the area of a rectangle and the circumference of a circle. That it might be wrong was not a possibility.

Both engineers in these two encounters are *grunt engineers*—the ones "in the foxholes" who actually apply the models. They are not research engineers, trained to probe and question. They have been trained to apply models unquestioningly in the rote fashion characteristic of the undergraduate curriculum in some engineering schools.

One fascinating example of engineering modeling of the impact of nature on human-made structures was the problem of fractures in World War II Liberty ships. Of the 2,700 vessels manufactured, 400 of them experienced hull fractures, 90 of which were serious and perhaps 20 of which resulted in the ship's sinking. All fracturing occurred in the cold water of the North Atlantic; the phenomenon was virtually nonexistent in ships traversing warm South Pacific waters. After a Liberty ship broke completely in two in 1943 while traveling between Siberia and Alaska and especially after another broke in two while docked in Boston Harbor in the winter of 1947, study of the phenomenon became a high priority. Before the Liberty ship problems, fatigue of metal plates was recognized, but low-temperature brittle fracture was not.

Eventually, mathematical modeling studies of the effect of the cold-water environment on metal plates identified the basis of the ship-fracture problem and a new field, *fracture mechanics*, was born. In hindsight, one might speculate about whether cold-water fracturing could have played a role in the sinking of the *Titanic.*

A World Without Models

Adaptive management has been discussed in several of the preceding chapters, including application in managing the Yucca Mountain nuclear repository and our disappearing fisheries. In the management of marine reserves for commercial fisheries, adaptive management involves trial and error rather than reliance on accurate predictions to determine the size and location of no-fish zones. The idea is to adjust the no-fish zones according to the success or failure of the initial reserve designation. If the sought-after increase in BOFFFs (big old fat female fish) is not achieved at first, the approach is altered. *Adaptive staging* or *adaptive management* could undoubtedly replace the quantitative predictive approach in many areas.

One huge area of quantitative mathematical model application is energy (coal, oil, nuclear). including availability, limits, costs, relative feasibility of solar, hydro, wind, nuclear and fossil fuel, energy and the environment, energy and war, and much more. Human behavior plays a big role here. For example, in the early 1970s Glenn Seaborg, chairman of the Atomic Energy Commission, projected a nuclear-electrical-generating capacity of 2,100 million kilowatts by the year 2000. The reality that came to be was 780 million kilowatts—the models didn't know that people would begin to object to nuclear power. Another model foiled by human behavior!

Vaclav Smil, a University of Manitoba geography professor and energy expert, argues that in energy affairs, model failures are a way of life. "The dismal record of long range forecasts . . . demonstrates convincingly that we should abandon all detailed quantitative point forecasts." The models used to forecast energy trends are referred to as *consolidative models*, or models in which the facts are brought together into a very complex model that is supposed to imitate the real world. (Each modeling specialty seems to have an independent lexicon of terms to describe its models. Use of the term *consolidative models* is clear evidence of the need to consolidate model terminology!) Smil cautions, however, that consolidative modeling doesn't work if there is "insufficient understanding" or if there are "irreducible uncertainties." The global energy system that Smil studies certainly falls into both of these categories, as do fisheries, groundwater flow, global climate change, beaches, and pit lake models. Smil believes, however, that modeling is here to stay and that we will continue to spend lots of effort and money on prediction but will never get better at it. "We will not do better as we try to include every conceivable factor in our assessments because many are either unquantifiable or their quantification cannot go beyond educated guessing."

Smil believes that a small calculator and the back of an envelope often can provide answers as useful as those obtained from modeling forecasts. He suggests that most of the grossly inaccurate forecasts of energy trends can be explained by two human truths. One is the mood of the moment, the tendency to be strongly influenced by current events and recent trends. The second is a fixation on new technology, preferred policies, and simple magical solutions.

He suggests that there are two non-modeling means of looking ahead that could be much more useful to society: *contingency scenarios* and *normative scenarios.*

In the contingency scenario approach, various possible scenarios are considered, ranging from those that are currently deemed likely to those viewed as most extreme. In the world of energy forecasting, extreme scenarios might include a global economic depression, general war in the Middle East, or terrorist attacks on pipelines. In the case of Yucca Mountain, the extreme scenarios would be a nearby volcanic eruption, a major earthquake, or a change in climate from arid desert conditions to a tropical rain forest. With this technique there is hope that no matter what scenario comes to pass in the future, an appropriate and rapid response has already been planned.

Smil suggests that society could determine norms of behavior, or normative scenarios, and action "to guide our long term paths toward the reconciliation of human aspirations with biospheric imperatives." This is an approach where humans strive to live in harmony with nature. Society determines what should happen and works in that direction rather than trying to predict what will happen and then riding along with events. When goals for a better life and a better environment are determined, society should then work toward achieving them.

Table 9.2 Some Distinguishing Characteristics of Scenario and Strategic Planning

SCENARIO PLANNING	STRATEGIC PLANNING OR MATHEMATICAL MODELING
qualitative input	quantitative input
exploits uncertainties	minimizes uncertainties
long-range planning	short-term planning
multiple answers	single answer
planning the future	predicting the future
hypothetical events	predetermined goals

The failed Kyoto Treaty, intended to globally reduce carbon dioxide emissions, was an example of the normative scenario approach. The same approach in the case of Yucca Mountain, given that we must have a repository for society's safety and well-being, would be the purchase of the property where radioactive waste might flow in case of a disaster and the moving of people off the property and out of harm's way.

University of Texas law professor Philip Bobbitt refers to the contingency scenario approach as *scenario planning*, "the construction of alternative scenarios rather than single point predictions in order not so much to predict the future as to help policy makers think about the future." Royal Dutch Shell greatly improved its fortunes by adopting scenario planning in the early 1970s. Among various scenarios the company considered was the rise of OPEC. The modeling approaches we have discussed in previous chapters are virtually all single-point predictions. Bobbitt refers to these as *strategic planning*. Table 9.2 lists some distinguishing characteristics of scenario and strategic planning.

Surely scenario planning (or the contingency scenario approach) holds promise as a replacement for the modeling approach currently practiced. If the management of the cod fishery had been based on scenario planning (and if politics hadn't intervened), the size and nature of both the nearshore and the offshore catch, as well as the abundance of the cod's food supply, the size of recruitment classes, and other factors could have all been incorporated into possible scenarios, and plans could have been laid for various "good" and "bad" events. Having done no such brainstorming, however, and depending solely on the size of the catch as the basis for management, mixed with a heavy dose of politics, the Canadian government allowed the world's greatest fishery to collapse. Other fisheries seem to be following this same disastrous path. Needless to say, it is possible for politics and special interests to spoil the best scenario planning.

What if contingency planning had been in place for abandonment of the Berkeley Pit in Butte, Montana? Would the state and the community have decided to prevent the world's largest cup of poison from forming by continuing to pump the pit dry? Would the decision have been to continuously decontaminate the water as the pit filled?

Contingency planning can be broadly applied to the use of quantitative mathematical models. For example, one (very likely) scenario is that the prediction by the model will be wrong. Planning for contingencies—if the pit water is more acidic than predicted, if the artificial beach disappears faster than assumed, if the fish numbers continue to decline, or if sea level rises faster than predicted—will place response plans in the hands of the responsible officials.

Quantitative applied models of processes on the surface of the earth for practical applications in engineering, policy, and environmental management should go the way of the passenger pigeon. Unfortunately, however, it is a fair prediction that applied quantitative modeling of complex systems will continue and even accelerate in our society, at least until public skepticism and recognition of failures arrest the trend. For those who understand the absurdity of quantitative applied models, some version of scenario planning and adaptive management may be the right path.

Thinking Like Physicists

Some energy companies like to hire distinguished physicists to devise mathematical models predicting future energy trends. Presumably this employment opportunity comes about because physicists are assumed to be applied mathematical whizzes, which they usually are. Physicists, however, are the last ones the industry should hire. Better to sign up scientists, like geologists, with a quantitative bent who deal with earth processes.

Physicists generally deal with a noncomplex world governed by rules and laws that are hard and fast, such as the principle of a ball rolling down an inclined plane, the constant rate of radioactive decay of uranium, and the predictable orbits of a planet around a sun. Once the physics of a ball rolling down an inclined plane is understood, prediction of the ball's velocity on planes set at various angles can be accurately and transparently accomplished. All who apply the laws of physics to this experiment will arrive at the same answers.

But complexity rules energy consumption, fuel prices, and coal production rates, and such complex energy systems cannot be quantitatively modeled. The mathematical models of different experts will come up with radically different predictions, as is apparent almost daily in TV business reports about the price of gasoline, heating-oil futures, and the Middle East petroleum outlook. The same is true for earth surface processes. The prediction of the future of beaches, fish abundance, the level of the sea, rates of shoreline erosion, and the future of invasive plants is entirely separate from the ordered, predictable, comfortable world of physicists.

Thinking like physicists and not recognizing complexity is what has allowed us to escape from reality through quantitative mathematical modeling. It has allowed us to predict the unpredictable. Ironically, in the unwritten pecking order of the sciences, physics and math are number one because they are the most quantitative, and geology bottoms out because it is dealing with many aspects of earth surface processes that cannot be quantified. The arrogance of some physicists who share this view is legendary. Ernest Rutherford, the father of nuclear physics, is credited with the observation that "all science is either physics or stamp collecting" (more recently, Robert McNamara referred to the qualitative approach as "poetry"). Unfortunately, as a result of this meaningless hierarchy, physics envy is a factor driving the rush to prediction by mathematics. If it is quantitative, like physics, then it has got to be sophisticated, like physics!

The quantitative trumping the qualitative has been with us since Lord Kelvin's time. This is what happened when the American Weather Service ignored qualitative hurricane warnings by the Cubans, who were reading cloud patterns instead of using modern weather-forecasting techniques. The result was that no one left Galveston before the 1900 hurricane struck and 6,000 souls perished.

Geology and biology are sciences that depend highly on field observations and expert intuition. Quantifying the behavior of organisms, the oceans, hill slopes, or sand grains with models requires stepping out of the intricate, dynamic, and supple world of nature into a wooden, unyielding, and inflexible world. It is a world where mathematical equations characterize events and processes, equations that can describe only a small part of the picture in very simple fashion. The intuition of an experienced scientist is gone. At best, only a small fraction of the processes that lead to the desired endpoint prediction can be considered.

The widespread use of coefficients (in the beach behavior models, for example), which in reality are fudge factors, and the very common and usually invisible practice of tuning or tweaking models to come up with the right answer, open the door to political pollution. Applied models, out there in the midst of politically sensitive societal issues, are easily moldable to favor a cause, be it a cost-benefit ratio, an environmental impact statement, the cause of a disease, the size of a fish population, or a prediction of future hazard potential. Add a fudge factor here and tweak the model there, and you have the "correct" answer. And the alterations are invisible to the managers who use the models.

The "transparency and openness to evaluation" required for invasive plant models by the National Academy of Sciences panel is rarely seen in the modeling literature. It is ironic that invasive plant biologists, in a specialty that does not depend on models, are the group suggesting the strongest restraints and highest standards for model use.

Qualitative modeling to help understand such processes has a bright and productive future. Here the intuition of scientists is not discarded. Experience is used for, among other things, figuring out what parameters in the process that's being modeled can be ignored. With a qualitative approach, these models can sort out the most important causes of shoreline erosion, help explain why sea level is rising, and speculate about the effectiveness of reduction of carbon dioxide emissions on global warming. But no models can predict with useful accuracy the rates of shoreline erosion, the rates of sea-level rise, or the impact of CO_2 reduction.

This means that we have to abandon our claims of accurate prediction of many natural processes. Instead of accepting a prediction of a two-foot rise in sea level over the next century, we might note that sea-level rise is likely to continue and that its acceleration is a good possibility. Instead of claiming that wastes from Yucca Mountain nuclear waste repository will not escape for 10,000 or 1 million years, the public might be informed that escape of the waste is unlikely in the next few hundred years, but when it does escape it will flow in this direction, to this location, and create the following problems. Rather than predicting that an artificial beach will last 8 years before more sand needs to be pumped onto it, engineers should announce that the artificial beach could last 6 years but also could disappear next week if the perfect storm occurs.

Differing degrees of societal damage can potentially be created by poor modeled predictions. The consequences of depending upon a model to correctly predict the configuration of new sandbars on the Grand

Canyon floor after a water release from Glen Canyon Dam are minute compared to the consequences of predicting catch levels for the Grand Banks cod fishery that employed 40,000 people. The consequences of failing to predict the life span of a nourished beach are small relative to under- or overestimating global sea-level rise.

Regardless of the societal importance of the modeling effort, if we wish to stay within the bounds of reality we must look to a more qualitative future, a future where there will be no certain answers to many of the important questions we have about the future of human interactions with the earth.

Even in the unlikely event that sometime in the remote future we will understand each of the numerous parameters and their interactions and feedbacks that control the event we are predicting, we shall never accurately predict the future. No one knows in what order, for what duration, from what direction, or with what intensity the various events that affect a process will unfold. No one can ever know.

"We all want progress," notes C. S. Lewis in his book *Mere Christianity*. "But progress means getting nearer to the place you want to be. And if you have taken a wrong turning [*sic*], then to go forward does not get you any nearer. If you are on the wrong road, progress means doing an about-turn and walking back to the right road; and in that case the man who turns back soonest is the most progressive man."

appendix

We have not included a single mathematical model in the text of this book. This is because we believe our conclusions can be made solidly without mathematics. Furthermore, we are writing for nonspecialists and nonmathematicians who we suspect would be repelled by differential equations and the likes (and wouldn't buy our book). It has been our experience that many people consider mathematical models to be opaque and impenetrable because the mathematics is beyond them. In our estimation this impassable nature of mathematics has allowed modelers to carry their trade far beyond the limits of reality, to the great detriment of our society.

Robert Moran, the geochemist concerned with pit lake quality, and Jim O'Malley, fishing industry representative, both view the mathematical modeling community as an unassailable and untouchable priesthood. We agree with this view. Because it is a priesthood, mathematical modeling has become a science that has advanced without the usual broad-based vigorous debate and criticism that characterize good science.

Critically reviewing models by examining assumptions rather than the math can bring a gale of fresh air into the modeling community. They need it. Criticism can only strengthen their specialty.