preface

According to Greek mythology, Zeus once released two eagles in order to find the center of the earth. One flew east and the other west. The birds met at Delphi, which lies on the slopes of Mount Parnassus. From about 1400 B.C. to A.D. 381, the Oracle of Delphi held sway at what was the most important shrine in all of Greece. The oracle could be more accurately described as a succession of priestesses, each given the title of Pythia. For twelve centuries the oracle played an influential role in ancient history and determined the course of empires.

Built around a sacred spring, the shrine to the oracle attracted people from all over Greece and far beyond, who came to pose their questions about the future to the Pythia. Her cryptic answers covered everything from optimal sowing and harvesting times to when an empire should declare war. As she responded to questions, seemingly in a trance, her inarticulate cries were interpreted and written down by an official scribe. In early times this transcription was rendered in hexameter verse, but later it was written in prose. The priest Plutarch said that the trance was the result of vapors, and indeed this may have been the case, for according to a recent geologic study, the presence of ethylene gas (once used as an anesthetic) has been detected in the vicinity of the spring.

The oracular responses were notoriously ambiguous, and their interpretation was often "deduced" only after the event to which they referred. Arguments over the correct interpretation of an oracle were common, but the oracle could always clarify or give another prophecy if more gold was provided. A good example is the incident before the Battle of Salamis, in which the Greeks defeated the Persians. The Pythia first predicted doom and later predicted that a "wooden wall" (interpreted by the Athenians to mean their ships) would save them.

Fast-forward 2,300 years and we find a world that still highly values and relies on prediction. Modern-day oracles are expected to provide predictions over a much wider range of things than the Oracle of Delphi could ever have imagined. In fact, with all the politicians, pundits, government agencies, stockbrokers, scientists, and academics offering their views today, we citizens are inundated with advice and suggestions derived from predictions about the future.

One type of prediction that the original Pythia seldom had to worry about has to do with processes on the surface of the earth. During the time of the Pythia, the earth was far less densely populated, and society had fewer machines to move soil, fight wars, or pollute the air and water. In the days of the American frontier you could start excavating a mine shaft in Montana whenever you wished, provided you could file the claim and pay for the dynamite. If you could make or buy a boat, all the fish in the sea were yours, provided you could catch them. And if you had an eroding shoreline in front of your house, you could build a seawall at will or dump a few dozen truckloads of sand or construction debris on the beach.

Times have changed. Before we can develop a new mine now, a vast amount of paperwork is required, including an environmental impact statement. Such statements are predictions of the ways in which the proposed project could affect the quality of air and water in the neighborhood, and the quality of life for plants and animals and humans alike. Shored up by the cries of distress from the mostly wealthy people who live next to beaches, the federal government began funding beach nourishment projects on Great Lakes and ocean shorelines. In order for a community to receive federal funding for an artificial beach, the calculation of a cost-benefit ratio is required, which in turn assumes an accurate prediction of how rapidly the artificial beach will disappear. Shock waves from the demise of the Grand Banks cod fishery, perhaps the world's greatest fishery for more than five hundred years, have bolstered the requirements for accurate estimates of fish stocks as a basis upon which to regulate fishing.

The widespread availability of computers, the requirement for environmental impact statements and cost-benefit ratios, and the dawn of mathematical models all arrived on the scene simultaneously in the final quarter of the twentieth century. Scientists in the 1960s and 1970s assured bureaucrats that the computer would make it possible to predict the outcomes of natural processes accurately. We don't know how to do it right now, they said, but fund us and we'll figure it out. There are still some scientists who claim successes—undaunted by several decades of the failure of certain mathematical models to provide the accurate answers that society needs.

At the beginning of the twenty-first century, predictive models of processes on the surface of the earth have come into widespread use. The recognition of complexity and chaos seems not to have diminished the still-rising star of modeling. Every year hundreds of cost-benefit ratios roll off the presses for federal engineering projects involving beaches, rivers, lakes, and groundwater flow. Engineers who have found great success in the use of models to predict the behavior of steel and concrete have applied modeling to the natural environment just as if nature were made up of construction materials with well-defined properties.

The environmental impact of various engineering activities 50 years into the future is calculated even more frequently than cost-benefit ratios are. The mother of all environmental impact predictions is the required assurance of 10,000 years of safety from the Yucca Mountain repository of the nation's radioactive waste. Billions of dollars have been spent at Yucca Mountain on the unrealistic goal of predicting what the climate and groundwater flow will be thousands of years from now. The American judiciary apparently is even more clueless than the scientists of the Department of Energy who are charged with proving the safety of Yucca Mountain—recently a federal court decreed that the prediction must cover 300,000 to 1 million years! The *New York Times* quotes an incredulous bartender in Las Vegas as saying, "The earth might not even be here a million years from now." The disappearance of the earth is perhaps not likely, but certainly over the next several hundred thousand years there will be two or three ice ages, the sea level will fall and rise by hundreds of feet, and Yucca Mountain will experience major changes in climate, perhaps an earthquake or two, maybe even a volcanic eruption. Undying faith in mathematics stilled the voice of scientific caution and skepticism that should have warned Congress and the judiciary that the predictive requirements they established for a repository at Yucca Mountain were impossible to achieve.

The reliance on mathematical models has done tangible damage to our society in many ways. Bureaucrats who don't understand the limitations of modeled predictions often use them. That was why the Bureau of Land Management allowed open-pit mines that, once abandoned, would eventually become "giant cups of poison." Models act as convenient fig leaves for politicians, allowing them to put off needed action on controversial issues. Fishery models provided the fig leaf for Canadian politicians to ignore the dying Grand Banks cod fishery. Agencies that depend upon project approvals for their very survival (such as the U.S. Army Corps of Engineers) can and frequently do find ways to adjust models to come up with correct answers that will ensure project funding. Most damaging of all is the unquestioning acceptance of the models by the public because they are assured that the modeled predictions are the state-of-the-art way to go.

If all this is true, how can people counteract the modeling craze? The supposition is that there is no way that ordinary people can argue with such sophisticated mathematics. But there is more to models than mathematics. There are parameters such as water velocity, temperature, wave height, rock composition and porosity, and many other factors that make natural processes work. And each of the parameters is represented in a model by simplifications and assumptions. This is the point at which the mathematically challenged among us can evaluate models and even question the modelers.

For example, the height of the waves striking a beach is an important control on the velocity of currents that carry sand away. Anyone who has spent time on a beach, however, knows that the waves vary widely from day to day and, of course, during a storm can be huge. So what number do you use in a model to represent such a variable parameter? The volume and flow rate of groundwater is an important factor in controlling the fate of nuclear waste at Yucca Mountain, Nevada, and the amount of rainfall will be critical in determining that rate. What number do you use in the model for the annual rainfall 100, 1,000, 10,000, or 1,000,000 years from now? After an open-pit mine is abandoned, the rate of flow of groundwater into the pit is critical to understanding whether or not the pit will be an environmental hazard, but the rate of flow into the pit will vary as acidic waters either dissolve rock and enlarge pores or precipitate minerals and reduce pores. Future rainfall amounts are also important.

How do you put all of this together and come up with a prediction of the composition of the pit lake 50 years from now? Or 100 years from now?

Years ago, in his capacity as a professor at Duke University, Orrin organized a graduate seminar in the Nicholas School of the Environment to look at mathematical models used in coastal geology. None of the class participants (including the professor) knew much about mathematical models. They decided to get to the bottom of the question of why the models seemed to come up with inaccurate predictions of the behavior of beaches.

What a revelation that seminar turned out to be! It became clear that beach modelers used models that had no demonstrable basis in nature. They employed "coefficients" that in reality were fudge factors to assure that the "correct" answer would be found, and no one looked back to see if the models actually worked. And no one was complaining. Neither the public nor the politicians knew or particularly cared, since the models were providing them with federal funds to stop beach erosion. And when the scope of the seminar was broadened beyond beaches, it became apparent that the problem existed in a wide variety of modeling efforts involved with all kinds of physical and biological processes concerned with the surface of the earth.

Clearly, the mathematical modeling community believed so strongly in models that it insisted on using them even when there was no scientific basis for their application. The discredited Bruun Rule model predicts how much shoreline erosion will be created by sea-level rise, and since no other model claims to do this, the Brunn Rule remains in widespread use. The maximum sustainable yield is a concept that fishery models are still using as a means to preserve fish populations despite the fact that the concept was discredited thirty-five years ago.

Participants in the seminar came to believe that an amazing statement by Jim O'Malley, a representative of the fishing industry, could be applied on a much broader front than fish models:

> I stress that the problem was not mathematics per se but the place of idolatry we have given it. And it is idolatry. Like any priesthood, it has developed its own language, rituals and mystical signs to maintain its status and to keep a befuddled congregation subservient, convinced that criticism is blasphemy. . . . Most frightening of all, our complacent acceptance of this approach shows that mathematics has become a substitute for science. It has become a defense against an appropriate humility, and a barrier to the acquisition of knowledge and understanding of our ocean environments. . . . When used improperly, mathematics becomes a reason to accept absurdity.

Linda has worked for both federal and state governments. Quantitative modelers, she independently observed, have an almost religiously fanatic outlook on the veracity of their models and brook little criticism. It is a characteristic we believe can be applied broadly to many natural-process modelers. The modeling modus operandi is shrouded in mystery, with necessary though poorly communicated assumptions made at each step along the way. In Linda's view, those who rely on the models for making policy decisions rarely understand the limitations of the models, much less are prepared to communicate such information to the public.

Qualitative models are used in trying to understand natural processes; here precise answers are not sought. Such models seek only trends, relative impacts, probable causes, directions of flow, timing of events. They consider and incorporate only the most important parameters of a process. They are not expected to produce accurate answers. These models often work and can be very useful. In this book we are concerned with the quantitative, "accurate" predictions made by mathematical models that are applied to societally important issues involving natural surface events on the earth. These models are expected to produce answers that are accurate enough to use for engineering and other applied societal purposes.

The book is intended to be read by non-specialists who are interested in nature and in the politics of working with the earth. We have not included equations here except (with some reluctance) for a few relatively simple examples in an appendix. Without resorting to mathematics, we make our point that applied quantitative mathematical models of earth processes cannot produce accurate answers. We evaluate assumptions behind the models, look at the nature of the field data that go into the models, evaluate model achievements, and examine the dialogue between modelers and their "customers." We are speaking to non-mathematicians like ourselves.