1 Philosophy and Approach

1.1 Introduction

This book is intended to introduce individuals with backgrounds in mathematics and science to elements of environmental modeling. In that regard, this material requires a transformation of thought processes if it is to be properly considered and assimilated.

Mathematics education traditionally involves exposure of students to mathematical theorems, identities, and concepts. These tools are then employed to solve problems. Problems encountered at a young age involve simple addition and subtraction. As the student acquires more skill, the range of techniques extends to multiplication, division, algebra, geometry, calculus, differential equations, complex analysis, and additional mathematical specializations. It seems fair to say that the overwhelming approach to these mathematical fields couples an explanation of a technique to a problem or equation that will succumb to the technique for its solution. Many mathematics texts provide a suite of problems that can be solved to demonstrate a particular technique; and answers to half the problems – typically the odd-numbered ones – are often found in the back of the book. It would be astonishing to find a listed answer to be "unsolvable" because the posed problem, indeed, cannot be solved exactly. Neither is a given solution designated as "approximate" unless the problem has been specifically employed to demonstrate properties of a truncated Taylor series, an asymptotic expansion, or some other analysis technique that explicitly makes use of approximations. Approximate solutions, like the exact ones, are prescribed to demonstrate the use of a mathematical technique.

Similarly, the background that an aspiring modeler brings to the field of environmental modeling includes elements of "exact" sciences. Problems posed in physics and chemistry books involve application of universal principles to provide understanding of the behavior of a system. Problems at the ends of chapters in introductory texts are solvable based on the principles discussed and illustrated in the text. Problems that cannot be solved exactly or that require insightful approximations specific to the system being considered are not offered. In many environmental modeling cases, equations are posed with the property that they can be solved exactly. The elements of approximation of physical phenomena are often skimmed over in favor of an equation that can be easily solved.

Based on these observations, it is the hypothesis here that perhaps the biggest challenge for a student in environmental modeling is acquisition of the insight and confidence to make reasonable physical approximations that lead to a mathematically approximate description of an environmental process that is useful for answering a question of interest.

Addressing hydrologic, atmospheric, and geophysical modeling problems from a scientific basis requires integration of physical understanding, mathematical skill, courage in making reasonable approximations, and transparency in identifying strengths, weaknesses, applicability, and limitations of models formulated, employed, and solved. From this perspective, embarking on environmental modeling considerations requires departing from the familiar comforts of well-defined problems for which a solution is in the back of the book or, at least, in someone's drawer. Rather one engages in tackling incompletely defined problems in an effort to understand the unknown elements of the past, present, or future and to learn where studies are needed to increase understanding. The needs to approximate, to span mathematics, science, and computational methods, to critique all elements of an analysis, and to admit limitations on what has been accomplished all contribute to making environmental modeling an exciting, yet uncomfortable, activity.

Because environmental modeling represents a departure from educational pedagogy employed in mathematics and science, it is important to identify explicitly the attitudes that must be adopted if one is to gain expertise, even in an introductory study of environmental modeling. Habits and expectations acquired through years of education in near-perfectly described physical phenomena making use of eminently solvable mathematical equations must be altered, perhaps reluctantly for some. Thus, in this chapter, rather than diving into the mathematics and physics, we will provide some preparatory thoughts intended to facilitate a transition from learning mathematics and science as separate disciplines to integrating these disciplines with each other and with an ability to make and understand approximations associated with modeling of environmental systems.

1.2 Elements of environmental modeling

"Environmental modeling" refers to a broad spectrum of approaches to studying the environment. It ranges from highly technical to purely descriptive. It includes examination of data for trends, development of equations that describe system processes, implementation of computer codes that describe system behavior, and construction of physical representations of natural systems that can be studied experimentally. The focus here is on presenting an understanding of how physical descriptions of system processes can be translated into mathematical analogues that provide an opportunity to investigate those processes. This focus is supplemented by some simple examples and calculations that add to understanding. This is not a book on computer programming. It is not a manual on applying off-the-shelf models. It is not a compendium of standard techniques. It is not a text on statistical modeling. The intention is to provide a sense for the meaning of mathematical expressions, a physical feel for their relations to the processes that they describe, and some confidence in working with mathematical solutions. If one is to begin to model, minimal prerequisites include calculus-based physics and calculus through differential equations. More substantive backgrounds might include fluid mechanics, heat and mass transport, partial differential equations, linear algebra, discrete analysis, numerical simulation, geochemistry, and other courses related to the chemistry, biology, mathematics, and physics of particular environmental systems. Novice modelers rarely have an extensive and broad background. We will therefore presume the minimal background and devote effort to filling in the mathematical and physical tools needed as the occasions arise. This approach is not employed as a substitute for advanced study, but will hopefully motivate further study.

Modeling of various sorts has gone on as long as humans have inhabited the earth. Speech is used to describe, or model, various experiences; art is used to model beauty, appearances, and emotions; computers are used to develop models of physical phenomena such as flows, chemical reactions, and heat transport processes. Yet as our tools have improved (e.g. vocabulary, mechanical tools, computational power), more insight and common sense than ever before are required to ensure that models are being used properly to transmit information and address important questions. For environmental considerations, the better tools that are available can help us develop more accurate and appropriate models, but they also allow us to get further off track! When used properly, models can be helpful complements to field and laboratory investigations in assessing phenomena of importance in the behavior of ecosystems. When used improperly, they can be misleading, dangerous, and detrimental to the cause of bringing sound science into play for informing public policy and benefitting humanity.

Environmental modeling, as considered here, consists of three elements: mathematics, description of environmental processes, and applications. These three elements are emphasized to varying degrees in each chapter, although typically one element will be predominant. In the earlier sections, some mathematical identities and definitions will be emphasized as these are fundamental to describing processes active in various applications, as well as for quantifying how good or bad these descriptions are. The mathematical sections are thus a means of tool acquisition that can support subsequent emphasis on model development and implementation. Accounting for the dynamics of environmental processes is rooted in conservation equations that can be used to describe systems. The approach is to use mathematical relations that describe physical processes and behavior, not mathematical correlations of data that can be mined for trends without consideration of system physics. The applications to be employed are admittedly simple. Their function is to demonstrate the kinds of results that can be obtained from a model, including issues relating to scale, data, and computer implementation. The applications are used not as much to tout what can be accomplished by models as to provide a balanced indication of the strengths, weaknesses, and reliability of models. Some concepts relating to model verification and validation, stability, and discretization error will be explored in the context of the processes described previously. Throughout the text, programming is minimal as gaining an understanding of modeling is a separate activity from merely exercising computer codes. The intention is that the text will knit together the important aspects of modeling so that, on working through this material, one will have an introductory appreciation for the modeling process balanced by a healthy regard for steps that must be taken to avoid model abuse. This mindset is essential as one embarks on more advanced modeling adventures where the processes and problems to be studied can be obscured by the overwhelming need to manage large data sets with sophisticated computer architecture.

We will conclude this chapter with several reflections on the overall goal of this book. These remarks, on one hand, are not intrinsically important to the development of the mathematics, processes, and modeling. However, they are meant to encourage the intellectual growth needed to expand from the study of mathematics, physics, and chemistry to the integration of these sciences with environmental analysis. Experience indicates that if one approaches a new field of study with the proper frame of mind, the work involved is more meaningful and enjoyable. The remarks here provide some motivation for the user of this book as to why the presentation is organized as it is and what the goals of this volume are. We believe that the views expressed are important enough that they should not be relegated to a preface but deserve the prime positioning as part of a chapter. Attitude, as well as aptitude, is essential to learning. Hopefully, the sections that follow will form the appropriate attitude.

1.3 Education vs. training

This book is intended to educate. A science-based educational environment provides preparation for the application of knowledge, enables an individual to learn new concepts or extensions of knowledge as they are needed, and reveals timeless principles that are the bases for developing technology. Thus, a foundation should be built that is both strong enough to allow insightful implementation of the plethora of currently available tools for modeling aspects of the environment (e.g. codes such as the HEC-RAS programs for river analysis, MODFLOW for subsurface systems, or the OLAM model for land–atmosphere interactions), as well as intellectual growth to be able to interact productively with models to be developed in the future. As technology advances at an accelerating pace, transformations of the type that have influenced scientific investigations over the last 40 years will be accomplished in ever-decreasing time frames. A foundation in timeless principles will make it possible for a scientist, engineer, or planner to move forward with those changes rather than be left behind tied to old technologies as they become obsolete. A strong foundation makes it possible to face successfully new intellectual challenges rather than become intellectually paralyzed by the mundane. Indeed, although our analysis tools have become more sophisticated, the need to manage the environment creatively – to reduce river flooding, to develop land, to provide fresh water supplies, to reduce particulates in air, to respond to climate change – has become even greater. To participate in this management, one must have a grasp of the underlying physical concepts that allow scientific understanding of the important issues as well as access to the available tools of analysis of those issues.

These considerations lead to a need to understand the difference between "education," which this book hopes to promote, and "training," which can be obtained, for example, by reference to a users' manual for a computer code. Unfortunately, it seems that today the traditional distinctive meaning of education as opposed to training is being blurred, and these terms are used almost interchangeably. We will be traditionalists on this point. Training is applied in various ways: to young children at about the age of two so that they can control their bodily functions; to pets so that they will react in a prescribed way to various stimuli (e.g. an electric fence) or commands. Training is employed to strengthen muscles, to enable them to move in certain ways; it is applied to hair so that it moves or stays in a particular style. Soldiers undergo basic training so that they will respond automatically, almost reflexively, to the various stresses of war. In all actions that proceed from training, thought is not paramount; creativity is precluded. The trained response follows within narrowly defined parameters.

Education, on the other hand, is not narrowing but broadening. Education in finance allows one to make reasoned decisions about the stock market behavior in changing economic conditions; education in poetry allows one to appreciate the creative use of language to express deep emotions or profound descriptions that touch individuals. Education in environmental modeling should not be reduced to grabbing formulas and performing multiplications such that one can come close to a target answer. Someone *trained* in modeling is able to solve problems that have been previously solved; he or she can match (some of?) the answers in the back of a book or on the web. He or she is able to turn to the correct page in a design manual or have a modeling program produce a colorful plot. Someone *educated* in environmental modeling is able to address new problems using continually developing tools, to obtain solutions to or insights about problems that have not previously arisen, and to pursue a course of action suggested by the analysis with confidence. An educated scientist may not know the precise page of a design manual to use, but he or she is able to make use of that manual and other tools that will become available over the course of a career as the need to solve problems in a variety of areas arises. An educated modeler can produce an elegant plot, but he or she also understands the physics, chemistry, and biology that underlie the plot as well as the strengths and weaknesses of the simulation depicted. An educated modeler is both a proponent of scientific analysis and a critic of its limitations. A trained modeler dispassionately produces results; an educated modeler produces results that are the basis for discussion, consideration, modification, insight, action, and reformulation of the model. It is more difficult, and at times more frustrating, to become educated in a particular area rather than merely to become trained. Nevertheless, education is the only viable route for the development of effective environmental modelers.

1.4 Principles ensuring education

To ensure that education, as opposed to training, takes place in the use of the material in this text, the following subsections indicate principles that should be observed as one encounters the various concepts and elements of modeling.

1.4.1 Education and expansion of thought processes

This text should be approached as an educational endeavor that requires a thoughtful approach to the subject matter, not with the expectation that it is a training activity that merely provides facility with a current computer code. The educational context is environmental modeling, but the thought processes to be explored are more important than the particular disciplinary context. This principle has a rather profound impact in the consideration of a subject that is evolving. The reader will be exposed to many useful techniques. It is possible to pose complementary exercises that merely involve “formula grabbing” or “black-box modeling” so that solutions can be obtained, perhaps providing a false sense of mastery of a topic. Instead, principles that underlie the problems studied are provided in necessarily abbreviated form. The educational approach requires that these principles receive additional attention so that the foundation on which analysis equations are built is clear. Typically, the study of environmental modeling is at least somewhat new for those studying this text. Despite that fact, the principles that are involved are the same as those used in fluid mechanics, biophysics, building design, structural analysis, and a large range of science and engineering disciplines and specializations. What is unique about environmental modeling is the context. It is important that the reader gains an appreciation for the common roots of analysis. This will allow for growth in a variety of areas of study without viewing all topics as completely new. It may also allow for beneficial transfer of techniques learned in one field of study to environmental analysis.

1.4.2 Challenge, persistence, critical analysis, and growth

An educational activity involves some challenge, persistence, critical analysis, and growth. Thus, study of this material will not always be easy and requires a departure from, or elevation above, a plateau of intellectual comfort. This issue goes to the heart of what constitutes a “good” presentation. From some points of view, a good presentation is one that requires little work, less thought, and a feeling that everything has been understood easily. Certainly, such a presentation provides a sense of comfort, but it is not consistent with the educational process. In fact, this approach is a disservice in that it disrupts what should be a process of immersion in trying to learn and think. For all of us, learning to think in new ways is difficult. It requires departure from comfortable knowledge. Venturing into new areas of study always begins with uncertainty. Will I be able to understand the topic? Will I gain insights or just be able to follow along? Why are we doing this? Where are we headed? First steps tend to be halting. They are much easier if someone is able to obtain assistance with those aspects of the new area which seem especially puzzling; and each person finds different aspects to be puzzling and challenging. Those studying this material are encouraged to seek assistance from colleagues when possible, to make use of other books or technical sources, to make an effort to master all the topics discussed. Learning occurs in the struggle with new concepts and ideas that are perplexing, not in hiding or ignoring subtleties in favor of just presenting the equation to be solved, getting to the last page of the book, or completing a course with an acceptable grade. The opportunity to learn when immediate clarity is not encountered should not be bypassed. A balance is needed that uses hard work and new insights to make the impossible manageable.

1.4.3 Learning through reading, discussion, problems, and critical assessment

Learning occurs through reading for understanding, discussion of issues encountered, application of knowledge through working problems, and critical assessment of the work performed. Without all of these elements, one is deluded into thinking the important aspects of modeling have been mastered if an attractive plot or movie of the results can be produced. Learning is not a passive activity; all learning is active. An individual will not learn to sufficient depth by simply reading this text. Learning requires taking advantage of ancillary opportunities that may be encountered. In fact, reading, discussion, problems, and critical assessment are inter-related rather than distinct activities. They contribute to each other and all provide clarification. This text contributes to the learning process, but by itself it cannot ensure that learning takes place.

Insightful questions are as valuable as insightful answers. Modeling that produces questions that focus the important issues surrounding a system under study is important and can even be the most important product of a modeling exercise. Answers to questions are found through discussion with others, considering alternative perspectives, work in the library, accessing the internet, modeling, data analysis, experimental inquiry, and plain hard work. Modeling conducted in a vacuum without recourse to these other elements of analysis cannot be successful. This text is incomplete in that it focuses only on the modeling aspect of a full problem analysis. Additional surprising and important insights can often be gained from discussions with colleagues or through questions.

1.4.4 Increase fundamental and general understanding

The objective of studying this material should be to increase fundamental and general understanding such that the details of a particular modeling exercise can be understood and the ability to learn more about the behavior of environmental systems is instilled. One should recognize that details are difficult to keep current; but if fundamental understanding exists, the details can be learned. One who engages the material in this book would do well to build the study around increasing ability to think critically within the context of the material provided. This approach will ensure that analysis skills are developed that will persist beyond the time frame of the encounter with the material here. Additionally, it will be easier to understand future approaches to problems and the issues addressed effectively in those approaches.

1.5 Conclusion

The purpose of this chapter is to provide the context and rationale for what is to follow. Environmental modeling is not an exercise that can be accomplished by a cookbook approach. Advancements in this area require a multifaceted approach, the willingness of the modeler to fully engage in the problem or problems being studied, and recognition that good modeling requires continual growth in ability and willingness to critique results. This book is only an introduction!

1.6 Problems

The objective of these questions is to encourage thoughtful consideration of the approach one might take to modeling and to ensuring that modeling capabilities continually improve.

1.1 A paper on environmental modeling was submitted to a journal. The submission contained the statement,

> A number of research papers have arisen that confuse the distinction [between kinematic and dynamic processes] and thus lead to ill-conceived and erroneous theoretical models.

The editor of the journal commented to the authors that he had concern over the way previous work was criticized, particularly because of use of the word "ill-conceived" which he saw as too direct and confrontational. He recommended that the quoted phrase be restated as ". . . thus lead to erroneous theoretical models." The authors responded to the editor,

> Models can be wrong or erroneous for many reasons. Among these reasons are basing them on wrong concepts, making mathematical error in derivation or implementation, using bogus data, or applying the model to an inappropriate system. All these models can be labeled "erroneous." It seemed to us that it is reasonable to label the first kind of erroneous model as "ill-conceived." The second type might be called "miscalculated." The third type might be called "fabricated," and the fourth type "misapplied." Our use of the word "ill-conceived" was intended to be descriptive of the type of error that impacted the model quality and thus to provide the reader with more information than the single word "erroneous" conveys.

An expert on writing and use of language, although with no background in modeling, commented on this exchange,

> "Ill-conceived" is different from – and, in the context [employed], vastly superior to – "erroneous." I suppose some extra-sensitive people would call it confrontational, but they need to toughen up.

(a) Comment on the above discussion including the strengths and weaknesses of each argument.
(b) How do you think the authors should have responded to the editor? Justify your recommendation.

1.2 In reviewing a manuscript on environmental modeling, a reviewer noted that a particular model was referred to as "erroneous." The reviewer suggested that a different adjective be used because there is a wide community that uses these models and there is no definitive model.

(a) Comment on the wisdom of the reviewer's recommendation.
(b) How should the authors respond to this review? Why?

1.3 A researcher has stated, "Once I have published an idea in the literature, I can't change it."

Comment on the wisdom of this approach for the researcher and for the technical community.

1.4 A problem exists when using models in the regulatory arena to ensure that models employed are reliable. However, the insistence on using a particular model can lead to controversy. Consider the statement,

> Models which were "approved" [by the EPA] more than a decade ago are still mandated in spite of their manifest inadequacies. Outdated models continue to be applied, at government insistence, to situations were [sic] accuracy is being sacrificed in the name of "consistency" or "conservatism." [231]

Propose some activities that could mediate the problem of stagnation in development of better models that is caused by the regulatory requirements to use generally accepted models that are considered reliable. Remember that there are economic and legal issues that impact this problem.