1 Introduction

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1.1 Introduction

There seems to be a tradition for books on complex systems to start from chapter zero (after Bar-Yam, 1997).

In one sense, everything in this book arises from the invention of the zero. Without this Hindu-Arabic invention, none of the mathematical manipulations required to formulate the relationships inherent within environmental processes would be possible. This point illustrates the need to develop abstract ideas and apply them. Abstraction is a fundamental part of the modelling process.

In another sense, we are never starting our investigations from zero. By the very definition of the environment as that which surrounds us, we always approach it with a number (non-zero!) of preconceptions. It is important not to let them get in the way of what we are trying to achieve. Our aim is to demonstrate how these preconceptions can be changed and applied to provide a fuller understanding of the processes that mould the world around us. From this basis, we provide a brief general rationale for the contents and approach taken within the book.

1.2 Why model the environment?

The context for much environmental modelling at present is the concern relating to human-induced climate change. Similarly, work is frequently carried out to evaluate the impacts of land degradation due to human impact. Such *application-driven* investigations provide an important means by which scientists can interact with and influence policy at local, regional, national and international levels. Models can be a means of ensuring environmental protection, as long as we are careful about how the results are used (Oreskes *et al.*, 1994; Rayner and Malone, 1998; Sarewitz and Pielke, 1999; Bair, 2001).

On the other hand, we may use models to develop our understanding of the processes that form the environment around us. As noted by Richards (1990), processes are not observable features but their effects and outcomes are. In geomorphology, this is essentially the debate that attempts to link process to form (Richards *et al.*, 1997). Models can thus be used to evaluate whether the effects and outcomes are reproducible from the current knowledge of the processes. This approach is not straightforward, as it is often difficult to evaluate whether process or parameter estimates are incorrect, but it does at least provide a basis for investigation.

Of course, understanding-driven and applications-driven approaches are not mutually exclusive. It is not possible (at least consistently) to be successful in the latter without being successful in the former. We follow up these themes in much more detail in Chapter 2.

1.3 Why simplicity and complexity?

In his short story 'The Library of Babel', Borges (1970) describes a library made up of a potentially infinite number of hexagonal rooms containing books that contain every permissible combination of letters and thus information about everything (or alternatively, a single book of infinitely thin pages, each one opening out into further

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pages of text). The library is a model of the universe – but is it a useful one? Borges describes the endless searches for the book that might be the 'catalogue of catalogues'! Are our attempts to model the environment a similarly fruitless endeavour?

Compare the definition by Grand (2000: 140): 'Something is complex if it contains a great deal of information that has a high utility, while something that contains a lot of useless or meaningless information is simply complicated.' The environment, by this definition, is something that may initially appear complicated. Our aim is to render it merely complex! Any explanation, whether it be a qualitative description or a numerical simulation, is an attempt to use a model to achieve this aim. Although we will focus almost exclusively on numerical models, these models are themselves based on conceptual models that may be more-or-less complex (see discussions in Chapters 2 and 17). One of the main issues underlying this book is whether simple models are adequate explanations of complex phenomena. Can (or should) we include Ockham's razor as one of the principal elements in our modeller's toolkit?

Bar-Yam (1997) points out that a dictionary definition of complex suggests that it means 'consisting of interconnected or interwoven parts'. 'Loosely speaking, the complexity of a system is the amount of information needed in order to describe it' (p. 12). The most complex systems are totally random, in that they cannot be described in shorter terms than by representing the system itself (Casti, 1994) – for this reason, Borges' 'Library of Babel' is not a good model of the universe, unless it is assumed that the universe is totally random (or alternatively that the library *is* the universe). Complex systems will also exhibit *emergent* behaviour (Bar-Yam, 1997), in that characteristics of the whole are developed (emerge) from interactions of their components in a non-apparent way. For example, the properties of water are not obvious from those of its constituent components, hydrogen and oxygen molecules. Rivers emerge from the interaction of discrete quantities of water (ultimately from raindrops) and oceans from the interaction of rivers, so emergent phenomena may operate on a number of scales.

A number of types of model complexity can be defined:

(a) Process complexity (complication) – the sophistication and detail of the description of processes (see Section 2.2.4).
(b) Spatial complexity – the spatial extent and grain of variation (and lateral flows) represented.
(c) Temporal complexity – the temporal horizon and resolution and the extent of representation of system dynamics.
(d) Inclusivity – the number of processes included.
(e) Integration – the extent to which the important feedback loops are closed.

Researchers have tended to concentrate on (a) whereas (b)–(e) are probably more important in natural systems.

The optimal model is one that contains sufficient complexity to explain phenomena, but no more. This statement can be thought of as an information-theory rewording of Ockham's razor. Because there is a definite cost to obtaining information about a system, for example by collecting field data (see discussion in Chapter 2 and elsewhere), there is a cost benefit to developing such an optimal model. In research terms there is a clear benefit because the simplest model will not require the clutter of complications that make it difficult to work with, and often difficult to evaluate (see the discussion of the Davisian cycle by Bishop 1975 for a geomorphological example).

Opinions differ, however, on how to achieve this optimal model. The traditional view is essentially a reductionist one. The elements of the system are analysed and only those that are thought to be important in explaining the observed phenomena are retained within the model. Often this approach leads to increasingly complex (or possibly even complicated) models where additional process descriptions and corresponding parameters and variables are added. Generally the law of diminishing returns applies to the extra benefit of additional variables in explaining observed variance. The modelling approach in this case is one of deciding what level of simplicity in model structure is required relative to the overall costs and the explanation or understanding achieved.

By contrast, a more holistic viewpoint is emerging. Its proponents suggest that the repetition of simple sets of rules or local interactions can produce the features of complex systems. Bak (1997), for example, demonstrates how simple models of sand piles can explain the size of occurrence of avalanches on the pile, and how this approach relates to a series of other phenomena (see Chapter 16). Bar-Yam (1997) provides a thorough overview of techniques that can be used in this way to investigate complex systems. The limits of these approaches have tended to be related to computing power, as applications to real-world systems require the repetition of very large numbers of calculations. A possible advantage of this sort of approach is that it depends less on the interaction and interpretations of the modeller, in that emergence occurs through the interactions at a local scale. In most systems, these local interactions are more realistic representations of the process than the reductionist approach that tends to be conceptualized so that distant, disconnected features act together. The reductionist approach therefore tends to constrain the sorts of behaviour that can be produced by the model because of the constraints imposed by the conceptual structure of the model.

In our opinion, both approaches offer valuable means of approaching understanding of environmental systems. The implementation and application of both are described through this book. The two different approaches may be best suited for different types of application in environmental models given the current state of the art. Thus the presentations in this book will contribute to the debate and ultimately provide the basis for stronger environmental models.

1.4 How to use this book

We do not propose here to teach you how to suck eggs (or give scope for endless POMO discussion), but would like to offer some guidance based on the way we have structured the chapters. This book is divided into four parts. We do not anticipate that many readers will want (or need) to read it from cover to cover in one go. Instead, the different elements can be largely understood and followed separately, in almost any order. Part I provides an introduction to modelling approaches in general, with a specific focus on issues that commonly arise in dealing with the environment. Following from background detail, which in turn follows the more basic material covered in Mulligan and Wainwright (2012), we have concentrated on providing details of a number of more advanced approaches here. The chapters have been written by leading modellers in the different areas, and give perspectives from a wide range of disciplines, applications and philosophical standpoints.

The 11 chapters of Part II present a 'state of the art' of environmental models in a number of fields. The authors of these chapters were invited to contribute their viewpoints on current progress in their specialist areas using a series of common themes. However, we have not forced the resulting chapters back into a common format as this would have restricted the individuality of the different contributions and denied the fact that different topics might require different approaches. As much as we would have liked, the coverage here is by no means complete and we acknowledge that there are gaps in the material here. In part this is due to space limitations and in part due to time limits on authors' contributions. We make no apology for the emphasis on hydrology and ecology in this section, not least because these are the areas that interest us most. However, we would also argue that these models are often the basis for other investigations and so are relevant to a wide range of fields. For any particular application, you may find building blocks of relevance to your own interests across a range of different chapters here. Furthermore, it has become increasingly obvious to us, while editing the book, that there are a number of common themes and problems being tackled in environmental modelling that are currently being developed in parallel behind different disciplinary boundaries. One conclusion that we would reach is that if you cannot find a specific answer to a modelling problem relative to a particular type of model, then looking at the literature of a different discipline can often provide answers. Even more importantly, they can lead to the demonstration of different problems and new ways of dealing with issues. Cross-fertilization of modelling studies will lead to the development of stronger breeds of models!

In Part III, the focus moves to model applications. We invited a number of practitioners to give their viewpoints on how models can be used or should be used in management of the environment. These six chapters bring to light the different needs of models in a policy or management context and demonstrate how these needs might be different from those in a pure research context. This is another way in which modellers need to interface with the real world – and one that is often forgotten.

Part IV deals with a current approaches and future developments that we believe are fundamental for developing strong models. Again the inclusion of subjects here is less than complete, although some appropriate material on error, spatial models and validation is covered in Part I. However, we hope this section gives at least a flavour of the new methods being developed in a number of areas of modelling. In general the examples used are relevant across a wide range of disciplines. One of the original reviewers of this book asked how we could possibly deal with future developments. In one sense this objection is correct, in the sense that we do not possess a crystal ball (and would probably not be writing this at all if we did!). In another, it forgets the fact that many developments in modelling await the technology to catch up for their successful conclusion. For example, the detailed spatial models of today are only possible because of the exponential growth in processing power over the last few decades. Fortunately the human mind is always one step ahead in posing more difficult questions. Whether this is a good thing is a question addressed at a number of points through the book!

Finally, a brief word about equations. Because the book is aimed at a range of audiences, we have tried to keep it as user-friendly as possible. In Parts II to IV we asked the contributors to present their ideas and results with the minimum of equations, but this is not always feasible. Sooner or later, anyone wanting to build their own model will need to use these methods anyway. If you are unfamiliar with text including equations, we would simply like to pass on the following advice of the distinguished professor of mathematics and physics, Roger Penrose:

> If you are a reader who finds any formula intimidating (and most people do), then I recommend a procedure I normally adopt myself when such an offending line presents itself. The procedure is, more or less, to ignore that line completely and to skip over to the next actual line of text! Well, not exactly this; one should spare the poor formula a perusing, rather than a comprehending glance, and then press onwards. After a little, if armed with new confidence, one may return to that neglected formula and try to pick out some salient features. The text itself may be helpful in letting one know what is important and what can be safely ignored about it. If not, then do not be afraid to leave a formula behind altogether.
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> Penrose (1989: vi)

1.5 The book's web site

As a companion to the book, we have developed a related web site to provide more information, links, examples and illustrations that are difficult to incorporate here (at least without having a CD in the back of the book that would tend to fall out annoyingly!). The structure of the site follows that of the book, and allows easy access to the materials relating to each of the specific chapters. The URL for the site is:

www.environmentalmodelling.net

We will endeavour to keep the links and information as up to date as possible to provide a resource for students and researchers of environmental modelling. Please let us know if something does not work and equally importantly, if you know of exciting new information and models to which we can provide links.

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