Editors John Wainwright and Mark Mulligan

Second Edition

Environmental Modelling

Finding Simplicity in Complexity

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Environmental Modelling

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Finding Simplicity in Complexity

Second Edition

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First Impression 2013

To Betty and John, for past and present inspiration, and Xavier and Lourenço for the future. (JW)

To my parents, David and Filomena, who taught (and teach) me so much and Sophia, Charlie and Olive who are very good at coping with all these whirring computers around the place. (MM)

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Preface to the Second Edition

Travelling through the UK following the wettest summer on record, one can see the direct and indirect effects of the dynamism of the environment and the responses to change, whether due to global-scale climate or local scale land use. Flood dis and still-inundated fields are the reminders of the dramas of months past. The impacts of such change are felt in many different ways across the globe, both in the moment of the event, or after a period of months or years – such as the expected significant rise of food prices that we are soon to endure. In this context, the aim of this book to understand environmental processes and use models to evaluate their effects remains as strong as ever. In what has been almost a decade since the first edition was assembled, the message of the original chapters remain as strong as ever, but the decade has also seen great advances in conceptual approaches, practical methods and technological advances for modelling. Practical applications of models always need to relate to the people affected by the systems simulated, but what is presented here are examples of the building blocks that can be used to such ends. It is left to the modeller to ensure that these blocks are put together in a robust but societally relevant manner.

In putting this second edition together, we realized very quickly that in wanting to provide more of a basic introduction to modelling, the structure was becoming very unwieldy. Therefore, we decided to take most of the original chapter 2 and develop it into a companion volume (or prequel, if you prefer) – *Building Environmental Models: A Primer on Simplifying Complexity* – which should appear in the next year or so. Some chapters from the original edition have been removed or rewritten and integrated into others to make way for chapters reflecting new developments and themes. We extend our warmest thanks to all of the authors for their collaboration and co-operation in this process. Discussions with, and inspirations from them all continue to inspire and inform our own work.

The basis of the book remains the work we both carried out in the Environmental Monitoring and Modelling Research Group in the Department of Geography, King's College London. Since the first edition, its original leader and our mentor, John Thornes, has sadly passed away, but we hope his work (see chapter 24) will remain an inspiration to environmental scientists for many years to come. Alan Dykes is now leading the production of an edited volume in his honour to show his legacy more fully. Also since the first edition, JW has become more peripatetic, which has provided an opportunity to try out ideas and materials on students in Sheffield, Strasbourg and Durham. We thank them all, as well as those from King's throughout the last two decades or so. The last word again goes to the apparently infinite patience of our editors at Wiley-Blackwell – Fiona Seymour and Lucy Sayer – in bringing this project to a successful conclusion.

John Wainwright and Mark Mulligan
Durham and London
October 2012

Preface to the First Edition

Attempting to understand the world around us has been a fascination for millennia. It is said to be part of the human condition. The development of the numerical models, which are largely the focus of this book, is a logical development of earlier descriptive tools used to analyse the environment such as drawings, classifications and maps. Models should be seen as a complement to other techniques used to arrive at an understanding, and they also, we believe uniquely, provide an important means of testing our understanding. This understanding is never complete, as we will see in many examples in the following pages. This statement is meant to be realistic rather than critical. By maintaining a healthy scepticism about our results and continuing to test and re-evaluate them, we strive to achieve a progressively better knowledge of the way the world works. Modelling should be carried out alongside field and laboratory studies and cannot exist without them. We would therefore encourage all environmental scientists not to build up artificial barriers between 'modellers' and 'non-modellers'. Such a viewpoint benefits no-one. It may be true that the peculiarities of mathematical notation and technical methods in modelling form a vocabulary which is difficult to penetrate for some but we believe that the fundamental basis of modelling is one which, like fieldwork and laboratory experimentation, can be used by any scientist who, as they would in the field or the laboratory, might work with others, more specialist in a particular technique to break this language barrier.

Complexity is an issue that is gaining much attention in the field of modelling. Some see new ways of tackling the modelling of highly diverse problems (the economy, wars, landscape evolution) within a common framework. Whether this optimism will go the way of other attempts to unify scientific methods remains to be seen. Our approach here has been to present as many ways as possible to deal with environmental complexity, and to encourage readers to make comparisons across these approaches and between different disciplines. If a unified science of the environment does exist, it will only be achieved by working across traditional disciplinary boundaries to find common ways of arriving at simple understandings. Often the simplest tools are the most effective and reliable, as anyone working in the field in remote locations will tell you!

We have tried to avoid the sensationalism of placing the book in the context of any ongoing environmental 'catastrophe'. However, the fact cannot be ignored that many environmental modelling research programmes are funded within the realms of work on potential impacts on the environment, particularly due to anthropic climate and land-use change. Indeed, the modelling approach – and particularly its propensity to be used in forecasting – has done much to bring potential environmental problems to light. It is impossible to say with any certainty as yet whether the alarm has been raised early enough and indeed which alarms are ringing loudest. Many models have been developed to evaluate what the optimal means of human interaction with the environment are, given the conflicting needs of different groups. Unfortunately, in many cases, the results of such models are often used to take environmental exploitation 'to the limit' that the environment will accept, if not beyond. Given the propensity for environments to drift and vary over time and our uncertain knowledge about complex, non-linear systems with threshold behaviour, we would argue that this is clearly not the right approach, and encourage modellers to ensure that their results are not misused. One of the values of modelling, especially within the context of decision-support systems (see Chapter 14) is that non-modellers and indeed non-scientists can use them. They can thus convey the opinion of the scientist and the thrust of scientific knowledge with the scientist *absent*. This gives modellers and scientists contributing to models (potentially) great influence over the decision-making process (where the political constraints to this process are not paramount). With this influence comes a great responsibility for the modeller to ensure that the models used are both accurate and comprehensive in terms of the driving forces and affected factors and that these models are not applied out of context or in ways for which they were not designed.

This book has developed from our work in environmental modelling as part of the Environmental Monitoring and Modelling Research Group in the Department of Geography, King's College London. It owes a great debt to the supportive research atmosphere we have found there, and not least to John Thornes who initiated the group over a decade ago. We are particularly pleased to be able to include a contribution from him (Chapter 18) relating to his more recent work in modelling land-degradation processes. We would also like to thank Andy Baird (Chapter 3), whose thought-provoking chapter on modelling in his book *Ecohydrology* (co-edited with Wilby) and the workshop from which it was derived provided one of the major stimuli for putting this overview together. Of course, the strength of this book rests on all the contributions, and we would like to thank all of the authors for providing excellent overviews of their work and the state-of-the art in their various fields, some at very short notice. We hope we have been able to do justice to your work. We would also like to thank the numerous individuals who generously gave their time and expertise to assist in the review of the chapters in the book. Roma Beaumont re-drew a number of the figures in her usual cheerful manner. A number of the ideas presented have been tested on our students at King's over the last few years – we would like to thank them all for their inputs. Finally, we would like to thank Keily Larkins and Sally Wilkinson at John Wiley and Sons for bearing with us through the delays and helping out throughout the long process of putting this book together.

John Wainwright and Mark Mulligan
London
December 2002

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Part I

Model Building

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.
>
> 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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2

Modelling and Model Building

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> Modelling is like sin. Once you begin with one form of it you are pushed to others. In fact, as with sin, once you begin with one form you ought to consider other forms . . . But unlike sin – or at any rate unlike sin as a moral purist conceives of it – modelling is the best reaction to the situation in which we find ourselves. Given the meagreness of our intelligence in comparison with the complexity and subtlety of nature, if we want to say things which are true, as well as things which are useful and things which are testable, then we had better relate our bids for truth, application and testability in some fairly sophisticated ways. This is what modelling does.
>
> (Morton and Suárez, 'Kinds of models', 2001)

2.1 The role of modelling in environmental research

2.1.1 The nature of research

Research is a means of improvement through understanding. This improvement may be personal but it may also be tied to development. We may hope to improve human health and wellbeing through research into diseases such as cancer and heart disease. We may wish to improve the design of bridges or aircraft through research in materials science, which provides lighter, stronger, longer lasting or cheaper (in terms of building and maintenance) bridge structures. We may wish to produce more or better crops with less adverse impact on the environment through research in biotechnology. In all of these cases research provides, in the first instance, better understanding of how things are and how they work, which can then contribute to the improvement or optimization of these systems through the development of new techniques, processes, materials and protocols.

Research is traditionally carried out through the accumulation of observations of systems and system behaviour under 'natural' circumstances and during experimental manipulation. These observations provide the evidence upon which hypotheses can be generated about the structure and operation (function) of the systems. These hypotheses can be tested against new observations and, where they prove to be reliable descriptors of the system or system behaviour, then they may eventually gain recognition as proven theory or general law as far as that is possible.

The conditions, which are required to facilitate research, include:

(a) a means of observation and comparative observation (measurement);
(b) a means of controlling or forcing aspects of the system (experimentation);
(c) an understanding of previous research and the state of knowledge (context); and
(d) a means of cross-referencing and connecting threads of (a), (b) and (c) (imagination).

Environmental Modelling: Finding Simplicity in Complexity, Second Edition. Edited by John Wainwright and Mark Mulligan.

2.1.2 A Model for environmental research

What do we mean by the term *model*? A model is an abstraction of reality. This abstraction represents a complex reality in the simplest way that is adequate for the purpose of modelling. The best model is always that which achieves the greatest realism with the least parameter complexity (parsimony) and the least model complexity. Realism can be measured objectively as agreement between model outputs and real-world observations, or less objectively as the process insight or new understanding gained from the model.

Parsimony (using no more complex a model or representation of reality than is absolutely necessary) has been a guiding principle in scientific investigations since Aristotle who claimed:

> It is the mark of an instructed mind to rest satisfied with the degree of precision which the nature of the subject permits and not to seek an exactness where only an approximation of the truth is possible

though it was particularly strong in Mediaeval times and was enunciated then by William of Ockham, in his famous 'razor' (Lark, 2001). Newton stated it as the first of his principles for fruitful scientific research in *Principia* as:

> We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

Parsimony is a prerequisite for effective scientific explanation, not an indication that nature *necessarily* operates on the basis of parsimonious principles. It is an important principle in fields as far apart as taxonomy and biochemistry and is fundamental to likelihood and Bayesian approaches of statistical inference. In a modelling context, a parsimonious model is usually the one with the greatest explanation or predictive power and the least parameters or process complexity. It is a particularly important principle in modelling because our ability to model complexity is much greater than our ability to provide the data to parameterize, calibrate and validate those same models. Scientific explanations must be both relevant *and* testable. Unevaluated models are no better than untested hypotheses. If the application of the principle of parsimony facilitates model evaluation then it also facilitates utility of models.

2.1.3 The nature of modelling

Modelling is not an alternative to observation but, under certain circumstances, can be a powerful tool in understanding observations and in developing and testing theory. Direct observation (as opposed to remote observation or estimation through spatial or temporal statistical inference) will always be closer to truth and must remain the most important component of scientific investigation. Klemeš (1997: 48) describes the forces at work in putting the modelling 'cart' before the observational 'horse' as is sometimes apparent in modelling studies:

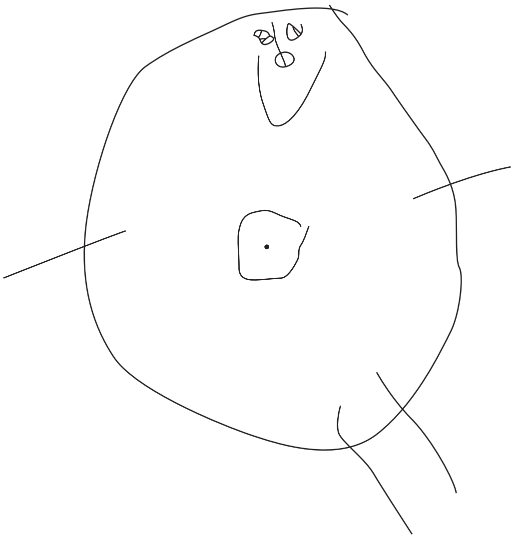
> It is easier and more fun to play with a computer than to face the rigors of fieldwork especially hydrologic fieldwork, which is usually most intensive during the most adverse conditions. It is faster to get a result by modeling than through acquisition and analysis of more data, which suits managers and politicians as well as staff scientists and professors to whom it means more publications per unit time and thus an easier passage of the hurdles of annual evaluations and other paper-counting rituals. And it is more glamorous to polish mathematical equations (even bad ones) in the office than muddied boots (even good ones) in the field.
>
> Klemeš (1997: 48)

A model is an abstraction of a real system; it is a simplification in which only those components that are seen to be significant to the problem at hand are represented in the model. In this representation, a model takes influence from aspects of the real system and aspects from the modeller's perception of the system and its importance to the problem at hand. Modelling supports the conceptualization and exploration of the behaviour of objects or processes and their interaction. Modelling is a means of better understanding and generating hypotheses. Modelling also supports the development of (numerical) experiments in which hypotheses can be tested and outcomes predicted. In science understanding is the goal and models serve as one tool in the toolkit used towards that end (Baker, 1998).

Cross and Moscardini (1985: 22) describe modelling as 'an art with a rational basis which requires the use of common sense at least as much as mathematical expertise.' Modelling is described as an art because it involves experience and intuition as well as the development of a set of (mathematical) skills (although many mathematicians would argue that mathematics also requires intuition and experience to be carried out well). Cross and Moscardini (1985) argue that it is intuition and the resulting insight that distinguish good modellers from mediocre ones. Intuition cannot be taught and comes from the experience of designing, building and using models. One learns modelling by doing modelling. The reader should look at the environmental issues presented in this book and abstract from them the key elements that might be required to build a useful simulation model. Abstraction is a difficult skill to acquire in adults (we tend to overcomplicate) though young children have the skill well honed as they operate their own mental models of how the world works before parents and teachers provide them with alternative models. A good exercise in judging your own abstraction skills may be carried out with a simple piece of paper. Think of all the faces that you know: the short round ones, the long thin ones, the European, African, Asian and South American ones; the ones with beards and those without. How might we abstract from this sea of faces a simple model for the human face? Try that on your piece of paper. Give yourself two minutes.

Our guess is that you made it too complex. The bare minimum we need is a circle, dots for eyes and a upwards facing curve for a mouth. The yellow smiley face is a good example and is one of the most common images in modern life. If you are not sure what we mean, do a Web search for 'yellow smiley face'. We do not need hair, ears, eyebrows, eyelashes or anything else to recognize this as a face. Indeed some real faces do not have those features (or at least they cannot be seen) so adding them to your model as a necessary condition for recognition as a face, reduces the generality of your model. Children are very good at abstraction as the four year old's image of a person in Figure 2.1 indicates: a single shape for the body, stick arms and legs, button eyes and nose and smiley mouth. Nothing else is needed as this is very clearly an abstraction of the human body. An element of bias is added as for this child the belly button is also an important component of the human form, hence it is in the model!

Arm yourself with a spreadsheet and turn your abstraction into numbers and simple equations. Play, examine, delete, add, think and play some more with the numbers and the equations. What can you learn about the system? What still confuses? Experience of this kind will help develop intuition and insight where it is lacking. We present you with a series of modelling problems on the web site that complements this book and going over them repeatedly will help further. The key to successful modelling is to be able to abstract carefully so that your model is on the one hand simple but on the other hand realistic enough to offer a solution to the problem at hand. Considering a cow as spherical may be appropriate for understanding some elements of how a cow works (Harte, 1985), but will not be all that helpful in understanding its locomotion!



Olive Mulligan, aged 4

Figure 2.1 Children are often very good at abstraction because they tend not to see things in the complicated ways that adults do (or to have complex preconceptions about them). This is a four year old's abstraction of a human – clearly recognizable, if not detailed (Courtesy of Olive Mulligan [aged 4]).

You are not new to modelling – everyone does it! All scientists use some form of conceptual or mental model of the data they work with. Even data are, in fact, models; they are simplified representations of (unobservable) processes, time and space, compared with the reality, all sensors form a model of reality. For example, a temperature sensor measures change in the level of a column of mercury as this level is linearly related to a change in temperature. The changing level of mercury *is* an empirical model for a temperature change. (Consider how different a digital thermometer actually is from an analogue one using mercury.) Your whole perception of reality is a model, not the reality itself. You are armed with a series of sensors for light in the visible spectrum (eyes) and certain wavelengths of sound (ears), which are only fractions of what can be sensed. Other animals have different perceptions of the same environmental characteristics because they have different sensors, but also a different mental model and context for decoding those signals. There is thus little difference between modelling and other scientific endeavours (and indeed life itself).

2.1.4 Researching environmental systems

According to some, we have crossed a geological boundary from the Holocene to the Anthropocene (Crutzen, 2002; Steffen *et al*., 2007; Zalasiewicz *et al*., 2010; Brown, 2011). The Holocene was an epoch of unprecedented stability that enabled complex societies, cultures, agricultures and infrastructures to be developed eventually supporting some seven billion people (Ruddiman, 2007). In the Anthropocene, humans are a major geological force generating planetary scale change in climate, land, water and ecosystems. Our increasing individual impacts on the environment coupled with our sheer numbers and their growth promises to put an end to this era of stability in favour of an epoch of unprecedented instability. In order to maintain and sustain water, food, shelter, livelihoods and culture we will need to manage our impact on nature much more effectively than ever before. We can only manage what we understand, so researching environmental systems is more important than ever.

Modelling has grown significantly as a research activity since the 1950s, reflecting conceptual developments in the modelling techniques themselves, technological developments in computation, scientific developments indicating increased need to study systems (especially environmental ones) in an integrated manner and an increased demand for extrapolation (especially prediction) in space and time.

Modelling has become one of the most powerful tools in the workshop of environmental scientists who are charged with better understanding the interactions between the environment, ecosystems and the populations of humans and other animals. This understanding is increasingly important in environmental stewardship (monitoring and management) and the development of increasingly sustainable means of human dependency on environmental systems and the services that they provide.

Environmental systems are, of course, the same systems as those studied by physicists, chemists and biologists but the level of abstraction of the environmental scientist is very different from that of many of these scientists. Whereas a physicist might study the behaviour of gases, liquids or solids under controlled conditions of temperature or pressure and a chemist might study the interaction of molecules in aqueous solution, a biologist must integrate what we know from these sciences to understand how a cell – or a plant – or an animal, lives and functions. The environmental scientist or geographer or ecologist approaches their science at a much greater level of abstraction in which physical and chemical 'laws' provide the rule base for understanding the interaction between living organisms and their nonliving environments, the characteristics of each and the processes through which each functions.

Integrated environmental systems are different in many ways from the isolated objects of study in physics and chemistry although the integrated study of the environment cannot take place without the building blocks provided by research in physics and chemistry. The systems studied by environmental scientists are characteristically:

Large scale, long term. Though the environmental scientist may only study a small time- and space-scale slice of the system, this slice invariably fits within the context of a system that has evolved over hundreds, thousands or millions of years and which will continue to evolve into the future. It is also a slice that takes in material and energy from a hierarchy of neighbours from the local, through regional, to global scale. It is this context, which provides much of the complexity of environmental systems compared with the much more reductionist systems of the traditional 'hard' sciences. To the environmental scientist models are a means of integrating across time and through space in order to understand how these contexts determine the nature and functioning of the system under study.

Multicomponent. Environmental scientists rarely have the good fortune of studying a single component of their system in isolation. Most questions asked of environmental scientists require understanding of interactions between multiple living (biotic) and nonliving (abiotic) systems and their interaction. Complexity increases greatly as number of components increases, where their interactions are also taken into account. Since the human mind has some considerable difficulty in dealing with chains of causality with more than a few links, to an environmental scientist models are an important means of breaking systems into intellectually manageable components and combining them and making explicit the interactions between them.

Non-laboratory controllable. The luxury of controlled conditions under which to test the impact of individual forcing factors on the behaviour of the study system is very rarely available to environmental scientists. Very few environmental systems can be rebuilt in the laboratory (laboratory-based physical modelling) with an appropriate level of sophistication to represent them adequately. Taking the laboratory to the field (field-based physical modelling) is an alternative as has been shown by the Free Atmosphere CO_2 Enrichment (FACE) experiments (Hall, 2001), BIOSPHERE 2 (Cohn, 2002) and a range of other environmental manipulation experiments. Field-based