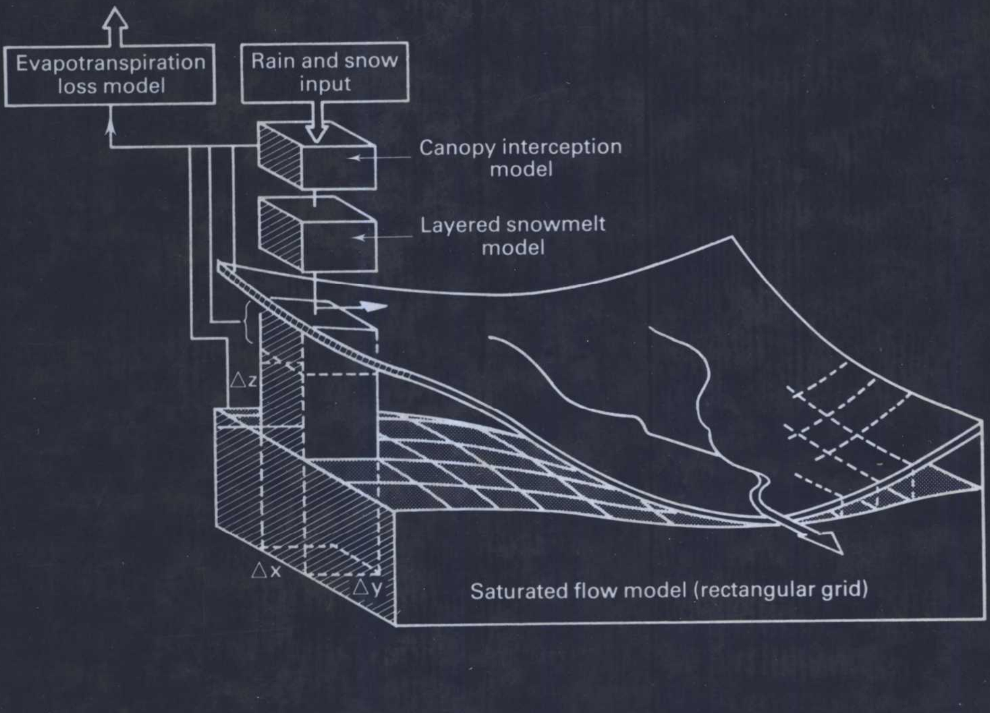
HYDROLOGICAL FORECASTING



Edited by
M. G. Anderson and T. P. Burt

Hydrological Forecasting

Edited by

M. G. Anderson
Department of Geography, University of Bristol

and

T. P. Burt
School of Geography, University of Oxford

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Hydrological Forecasting

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A series in Geomorphology

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Edited by
M. G. Anderson, *Department of Geography, University of Bristol*
and
T. P. Burt, *School of Geography, University of Oxford*

Series preface

This is the fourth book in the present series *Landscape Systems*. Each is intended to present the state of the art in a topic related to the earth's surface in its natural state and as modified by man. Like other volumes in the series, *Hydrological Forecasting* has been written by a number of authors, each of whom is contributing within his own specialist field, but within the context of an overall editorial framework to guarantee proper coverage of the subject at the current research level. This approach provides a comprehensive high level textbook written by acknowledged experts, revealing current controversy and current research directions without needless duplication. The series covers topics in geomorphology, but is almost equally relevant to hydrology, soil science, agriculture and forestry.

Previous books in the *Landscape Systems* series have been on *Hillslope Hydrology*, *Soil Erosion* and *Slope Instability*. *Hydrological Forecasting* covers a wider range of topics than *Hillslope Hydrology*, being concerned with all components of the catchment hydrological cycle, but in the narrower context of forecasting models. This is seen as an area of great interest and rapid development towards models which give due weight to all components of the water balance. At the same time, there has been some retreat from fully distributed models, which are now considered to offer little advance in forecasting ability at excessive cost in their data requirements.

Research on our physical environment is still in a phase of rapid development on incomplete foundations, particularly for the field scale of interest at perhaps a hectare–hour level of spatial and temporal resolution. At these scales our detailed knowledge of physics and chemistry is so complicated by the need to obtain aggregate behaviour for a combination of variable spatial units that it is in many cases largely irrelevant. For many cases we can rely on no relevant and secure foundations beyond statements of mass balance. The problem is no less trivial than the problem of changing from quantum to aggregate descriptions of a solid body, and we are still some way from its solution. It is exacerbated by the practical difficulties of fully representing field variability in material properties, or in water or sediment flows. I believe that the best prospect of major advances in our understanding is through the joint endeavours of workers in many related fields, including both traditionally laboratory and traditionally field scientists.

This series is intended to help build bridges between neighbouring disciplines, and to interest a wider scientific community in our common problems, and so stimulate the detailed thought and discussion which lead to scientific advance.

PROFESSOR MIKE KIRKBY

Preface

The growth in recent years of hydrological forecasting techniques, both 'hardware' and 'software' in character, has been quite outstanding. The primary objective of this volume is to outline at the postgraduate level the current state of forecasting capability in the major hydrological areas relevant to the watershed, as opposed to the hillslope, scale.

The motivation for this theme originated in a lecture series the senior editor gave at Bristol in 1981. Since that time, we have received the help and encouragement not only of contributors but also of many colleagues and friends, which has resulted in the current volume.

It is clear from many of the contributions that we still have much to learn regarding the balance between model performance and required objectives. It is only by critically appraising current capabilities that we can hope to move logically towards model redesign to meet specific forecasting goals. We hope that this volume provides a basis for encouraging research in this direction.

MALCOLM G. ANDERSON
BRISTOL

TIM BURT
OXFORD

Contributors

S. AMBRUS, *Water Resources Research Centre, VITUKI, Krassay J. I., H-1095 Budapest, Hungary*

M. G. ANDERSON, *Geography Department, University of Bristol, University Road, Bristol BS8 1SS, UK*

K. BEVEN, *Institute of Hydrology, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB, UK*

J. M. BLACKIE, *Institute of Hydrology, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB, UK*

T. P. BURT, *School of Geography, University of Oxford, Mansfield Road, Oxford, OX1 3TB, UK*

D. R. DAVIS, *Department of Hydrology and Water Resources, College of Earth Sciences, University of Arizona, Tucson, Arizona 85721, USA*

L. DUCKSTEIN, *Department of Hydrology and Water Resources, College of Earth Sciences, University of Arizona, Tucson, Arizona 85721, USA*

C. W. O. EELES, *Institute of Hydrology, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB, UK*

D. L. FREAD, *Office of Hydrology, National Weather Service, Gramax Building W23, 8060 13th Street, Silver Spring, Maryland 20910, USA*

J. HANKS, *Department of Soil Science and Meteorology, Utah State University, Logan, Utah 84322, USA*

G. L. HUEBNER, *Department of Meteorology, Texas A & M University, College Station, Texas 77843, USA*

D. HUFF, *Building 1505, Oak Ridge National Laboratory, PO Box X, Oak Ridge, Tennessee 37830, USA*

M. J. KIRKBY, *School of Geography, The University, Leeds LS2 9JT, UK*

L. KONIKOW, *USGS, 431 National Center, Reston, Virginia 22092, USA*

H. LAVEE, *Institute of Earth Sciences, The Hebrew University, Jerusalem 9104, Israel*

E. MORRIS, *Institute of Hydrology, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB, UK*

P. E. O'CONNELL, *Department of Civil Engineering, University of Newcastle-upon-Tyne, 6 Kensington Terrace, Newcastle-upon-Tyne NE1 7RU, UK*

E. G. PATTEN JR, *USGS, 431 National Center, Reston, Virginia 22092, USA*

T. SCHMUGGE, *NASA Goddard Laboratory for Atmospheric Sciences, Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*

T. D. STEELE, *In Situ Inc, 7401 W Mansfield Avenue, Suite 114, Lakewood, Colorado 80235, USA*

W. T. SWANK, *Building 1505, Oak Ridge National Laboratory, PO Box X, Oak Ridge, Tennessee 37830, USA*

C. A. TROENDLE, *Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, 240 West Prospect, Fort Collins, Colorado 80521, USA*

E. F. WOOD, *Department of Civil Engineering, Princeton University, Princeton, New Jersey 08544, USA*

A. YAIR, *Institute of Earth Sciences, The Hebrew University, Jerusalem 91904, Israel*

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Hydrological Forecasting
Edited by M. G. Anderson and T. P. Burt

CHAPTER 1

Modelling strategies

M. G. Anderson* and T. P. Burt†

*Department of Geography, University of Bristol, UK
†School of Geography, University of Oxford, UK

> Despite the attention which this problem has attracted over many years, the present position is far from satisfactory. Few hydrologists would confidently compute the discharge hydrograph from rainfall data and the physical description of the catchment. (Nash and Sutcliffe, 1970)

1.1 MODELLING OBJECTIVES

The scientific tradition of generalization is long established in hydrology. Dooge (1977) has traced the 'rational method' for the prediction of flood peaks back to Mulvaney (1851). Sherman (1932) introduced the concept of the unit hydrograph, a methodology which was to dominate hydrology for a quarter of a century, and one which is still in widespread use today. More recently, the advent of high-speed computers has led to a proliferation of runoff models which achieve generalization of reality using a variety of mathematical approaches.

All models seek to simplify the complexity of the real world by selectively exaggerating the fundamental aspects of a system at the expense of incidental detail. In presenting an approximate view of reality, a model must remain simple enough to understand and use, yet complex enough to be representative of the system being studied. When choosing which type of mathematical model to use in order to solve a particular problem, the hydrologist faces a major dilemma: the consistently successful use of black-box hydrological models (see, for example, Chapter 15) has shown that models need contain little or no relationship to physical reality. Indeed, as Klemes (1981) notes, even a moderate hydrological insight can become a nuisance which only detracts from the efficient application of advanced statistics. In contrast, the development of theoretical models, which do possess some physical basis, offers the hydrologist two particular advantages: first, such models provide a real possibility of successful application over a wide range of conditions and sites; and second, such models can aid our understanding of natural processes and systems, and can thus provide a bridge between theory and data. For example, Konikow and Patten (Chapter 9) show how the use of a theoretical model improved their understanding of the groundwater system, highlighting properties of the system which should perhaps be theoretically predictable, but which, given the complexity of the real world, only become apparent through the use of a theoretically based simulation model. Renard *et al.* (1982), in reviewing a large number of models currently available for use in small watersheds, note that many of the models are site-specific, and contain simplifications and assumptions which preclude their use universally. Kuhn (1961) has argued that all experimental sciences progress from empirical generalizations to theoretically based explanations. In this respect the science of hydrology is no different; in the short term, regression and transfer function models are likely to provide quite adequate predictions at a particular site. Even so, it is clear that in many areas of hydrology the development of physically based theoretical models reflects a general desire to provide more widely applicable models.

1.2 CHOICE OF MODEL

A possible methodology for selecting a mathematical model is given in Figure 1.1. The scheme emphasizes the dependence of the entire modelling exercise upon a clear definition of the problem to be solved, and upon the data base which is available to describe the physical system. The general environment within which the choice of a particular model is made may be summarized under four main headings:

1.2.1 The aims and scope of modelling

The aim of most hydrological modelling is to provide a prognosis of the future performance of a hydrological system; such a judgement may be made with respect to real-time (*forecasting*) or without specific time reference (*prediction*). Models may be used to describe a whole range of hydrological processes and water uses, as shown in Table 1.1. A given model may require inputs of one or several of runoff process elements; model output may be prescribed for single or multiple outputs, although in most models the ability to predict stream discharge remains most important. When modelling water quality, hydrological processes are likely to provide the basic foundation of the model (Donigian and Crawford, 1976; Steele, Chapter 10, especially section 10.3). The overall structure of this text reinforces this general point with a substantial emphasis placed on runoff process element forecasting, which then forms the basis for the progression to water quality, real-time and management

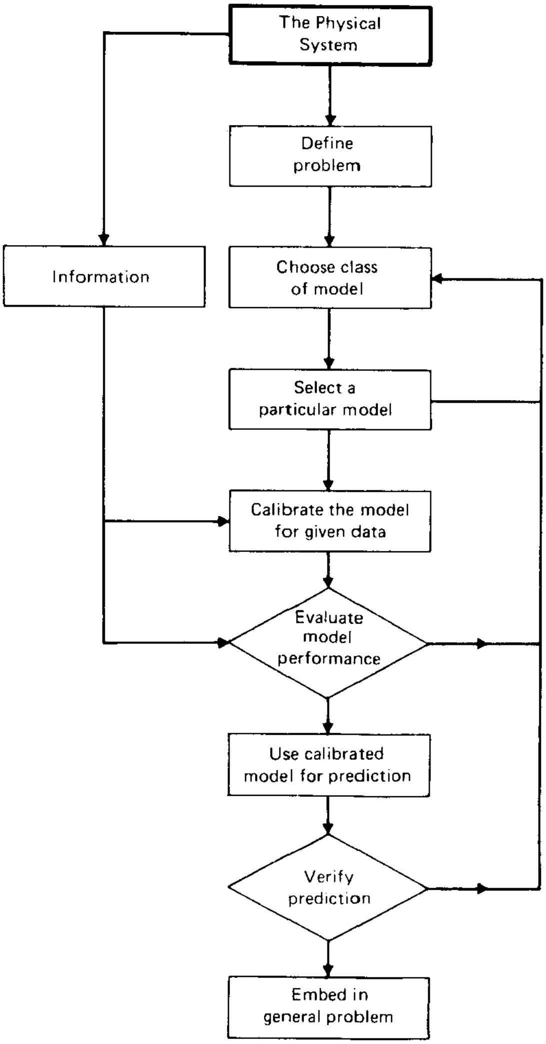

Figure 1.1 A possible methodology for selecting a mathematical model (after Dooge, 1981)

forecasting (see Table 1.1). The spatial extent and time base of the model will reflect both the modelling objectives and the degree of realism sought in the model. The entire (lumped) catchment is perhaps still the most common spatial unit encountered with a primary division into watershed (or hillslope) and channel domains being made once a spatially distributed approach is required; Chapters 11, 13, and 14, respectively by Blackie and Eeles, Beven and Fread, describe these various approaches. Many models consider only conditions at one point (e.g. the snowmelt point models described by Morris (Chapter 7), and the Prosper evaporation model described in Chapter 6 by Huff and

Table 1.1 The range and extent of hydrological modelling

Modelling elements identified by Dooge (1981)	Reference in this book
(i) Runoff process elements	Chapters 2, 5
soil moisture	Chapter 3
hillslope runoff	Chapter 4
precipitation	Chapter 6
evapotranspiration	Chapter 9
groundwater	Chapters 11, 12, 13
catchment runoff	Chapter 14
channel flow	
(ii) Water quality elements	
physical water quality	Chapter 10
chemical water quality	
biological water quality	
(iii) Water resource models	Chapters 14, 15, 16 as well as applications in other chapters, e.g. 7,8.
water supply	
pollution control	
hydropower	
irrigation	
flood control	
land drainage	
navigation	
recreational use	
ecological conditions	
(iv) Model extent	Considered where relevant in selected chapters
conditions at a point	
upland watershed domain	
channel domain	
lumped catchment response	
(v) Model time base	Chapter 15 and other chapters where relevant
single events or time periods	
continuous forecasting	
'forecasting' vs. 'prediction'	

Swank). The major difficulty encountered is to synthesize and aggregate the results of point-modelling to provide a realistic input to catchment-scale models (Kirkby, Chapter 3). The time-base of hydrological models is commonly divided between single flood events and continuous forecasting. As might be expected, the desire for greater detail of time and space to be included in a model brings with it a commensurate requirement for a more sophisticated model structure.

1.2.2 Choice of model

Taking all aspects of hydrological investigations, there are three types of model structure that are classically identified:

Black-box models

These contain no physically based transfer function to relate input to output. Such models depend upon establishing a statistical correspondence between input and output, and include a number of successful approaches including the unit hydrograph, extreme frequency analysis, regression analyses, and real-time forecasting models as described by Wood and O'Connell in Chapter 15. Within the range of data analysed, such models may be highly successful, often because the formal mathematical structure carries with it an implicit understanding of the underlying physical system. However, as Klemes (1981) points out, in extrapolating beyond the range of actual experience, this physical 'anchor' is lost, and the prediction then relies on mathematical technique alone; because of the inherent linearity of many black-box models, such extrapolation may well be of dubious worth. It is ironic that extreme events, the focus of so much predictive modelling prove so difficult to predict using simple input– output models.

Conceptual models

These occupy an intermediate position between the deterministic approach and empirical black-box analysis. Such models are formulated on the basis of a simple arrangement of a relatively small number of components, each of which is a simplified representation of one process element in the system being modelled. Each element of the model will consist of a non-linear reservoir in which the relationship between outflow (Q) and storage (S) is given by

$$S = K \cdot Q^n$$

where K and n represent constants. The non-linear form of such models reflects the thresholds present in hydrological systems which cannot be adequately incorporated within a linear model. The source of this non-linearity is often soil moisture conditions, whether controlling groundwater recharge or surface/subsurface storm runoff. Thus even single-reservoir, lumped models must include some reference to soil moisture; the isolated event model IEM4 (NERC, 1975; Blackie and Eeles, Chapter 11) uses soil moisture deficit (SMD) to calculate net rainfall; in Topmodel (Beven and Kirkby, 1979; Beven, Chapter 13), soil water storage is used to calculate the area of a catchment producing surface runoff, thereby incorporating the partial area concept into