TIME SERIES MODELLING
OF
WATER RESOURCES
AND
ENVIRONMENTAL SYSTEMS

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TIME SERIES MODELLING
OF
WATER RESOURCES
AND
ENVIRONMENTAL SYSTEMS

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To Our Wives

Sheila and Maree

and

Our Children

Melita, Lloyd, Conrad, Warren

and

Jonathan

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PREFACE

In order to understand and model how one or more inputs to a given system affect various outputs, engineers and scientists take measurements over time. For a given input or output variable that is being monitored, the set of observations appearing in chronological order is called a time series. In **time series modelling and analysis**, time series models are fitted to one or more time series describing the system for purposes which include forecasting, simulation, trend assessment, and a better understanding of the dynamics of the system. The kinds of systems which can be studied from a time series modelling viewpoint range from a purely socioeconomic system where econometricians may wish to determine how leading indicators can be used to forecast the future performance of the economy of a country, to a completely physical system for which engineers may wish to ascertain how land use changes have affected the environment.

This is a book about time series modelling of water resources and environmental systems. From the area of **stochastic hydrology**, consider for example, how time series analysis may be employed for designing and operating a system of hydroelectric facilities. After fitting stochastic or time series models to pertinent hydrological time series such as sequences of riverflows, precipitation and temperature measurements, the fitted models can be employed for simulating possible hydrological inputs to the hydroelectric system. These inputs can be used for testing the economical and physical performance of various alternative designs of the system in order to select the optimal design. Subsequent to the construction of the system of reservoirs, stochastic models can be employed for forecasting the input flows to the system and the demand for electrical consumption, in order to ascertain an optimal operating policy which maximizes the hydroelectrical output subject to physical, environmental, economical and political constraints.

As another example of the use of time series modelling in the environmental sciences, consider the use of time series models for the **trend assessment** of water quality time series. Land use changes such as increased industrialization and the cutting down of forests may cause water quality variables in a river to deteriorate over time. To model the trends and estimate their magnitudes, appropriate time series models can be employed. In Part VIII of the book, the intervention model is suggested as a flexible model for use in an **environmental impact assessment** study. From a qualitative viewpoint, the intervention model for a water quality study can be written as:

Water Quality Variable = **Intervention Effects** + **Riverflows** + **Other Water Quality Variables** + **Missing Values** + **Noise**

In the above relationship, the output water quality variable on the left may represent a phenomenon such as phosphorous levels in a river. The intervention effects are modelled as the changes in the mean level of the phosphorous time series due to the external interventions. The input series may consist of riverflows and other water quality variables such as temperature and turbidity. If there are not too many missing values, the intervention model can be used to estimate them. Finally, the noise term in the intervention model captures what is left over after the other model components are accounted for. Because the noise is often modelled as an ARMA (autoregressive-moving average) model, it can properly handle any autocorrelation which may be present. Hence, one does not have to assume that this noise is white.

The areas of **stochastic hydrology** and **statistical water quality modelling** constitute two domains that are of direct interest to scientists and engineers who wish to study water resources as well as other related environmental systems. As illustrated above, within each domain, time series modelling possesses widespread applicability. Rather than treating these areas separately, this book amalgamates these two subfields under the overall field called environmetrics. As explained in Section 1.1 of the first chapter, **environmetrics** is the development and application of statistics in the environmental sciences. Because various kinds of time series models constitute the main type of statistical tools described in this book, the title of the book is appropriately given as **"Time Series Modelling of Water Resources and Environmental Systems."** A variety of other statistical methods such as **graphical techniques, nonparametric trend tests** and **regression analysis** are also presented in the book.

To demonstrate how the time series models and other statistical techniques are applied in practice, **practical applications** to riverflow, water quality and other types of environmental time series are given throughout the book. However, the reader should keep in mind that the techniques can be applied to time series arising in fields falling outside the environmental areas of this book. Accordingly, the types of **Professionals** who may wish to use this book include:

Water Resources Engineers
Environmental Scientists
Hydrologists
Geophysicists
Geographers
Earth Scientists
Planners
Economists
Mechanical Engineers
Systems Scientists
Chemical Engineers
Management Scientists

Within each professional group, the book is designed for use by:

Teachers
Students
Researchers
Practitioners and Consultants

When employed for teaching purposes, the book can be used as a course text at the **upper undergraduate or graduate level**. Depending upon the number of topics covered, it can be utilized in a **one or two semester course**.

As can be seen from the Table of Contents, and also **Table 1.6.1**, the book is divided into **ten major Parts** having a total of **twenty-four Chapters**. For convenience, the titles of the ten Parts are listed in **Table P.1**. The book contains descriptions of **specific statistical models and methods** as well as **general methodologies** for applying the statistical techniques in practice. The only background required for understanding virtually all the material presented in the book is an introductory one semester course in probability and statistics.

Table P.1. Ten main Parts in the book.

Part Numbers	Part Titles
I	Scope and Background Material
II	Linear Nonseasonal Models
III	Model Construction
IV	Forecasting and Simulation
V	Long Memory Modelling
VI	Seasonal Models
VII	Multiple Input-Single Output Models
VIII	Intervention Analysis
IX	Multiple Input-Multiple Output Models
X	Handling Messy Environmental Data

Depending upon the background and interests of the reader, Section 1.6.2 describes the **various routes** that can be followed for exploring the countryside of ideas presented in the book. Consequently, in the Preface only the main topics covered in the book are highlighted. In general, the book progresses from describing simpler to more complicated models in order to model more complex types of environmental data sets.

A summary of the main contents of each Part in the book is presented at the start of each Part. Consequently, the reader may wish to **read each of the ten summaries** before referring to detailed descriptions of techniques and methodologies presented in each chapter. Within **Part I**, the **scope** of the book and some **basic statistical definitions** that are useful in time series modelling are given in Chapters 1 and 2, respectively. As explained in Chapter 1, statistical methods can be used to enhance the **scientific approach** to studying environmental problems which should eventually result in better overall **environmental decisions** being made at the political level of decision making. In order to give the reader some tools to work with, various classes of linear nonseasonal models are presented in **Part II**. More specifically, in Chapter 3 the **AR** (autoregressive), **MA** (moving average) and **ARMA** models are defined and some of their important theoretical properties, such as their theoretical autocorrelation structures, are derived. As is the case with all of the models defined in the book, special emphasis is placed upon highlighting **theoretical properties which are useful in practical applications**. The models of Chapter 3 are designed for application to **stationary nonseasonal time series** for which the statistical properties do not change over time. In Chapter 4, the **ARIMA** (autoregressive integrated moving average) model is defined for application to a **nonstationary nonseasonal time series** where, for instance, the level of the series may increase or decrease with time. Other kinds of time series models are presented in Parts V to IX of the book. A list of all the time series models described in the book is given in **Table 1.6.2**. However, before presenting other kinds of time series models after Part II, some practical aspects of time series modelling are described. In particular, **Part III** explains how the nonseasonal models of Part II can be fitted to yearly time series by following the identification, estimation and diagnostic check stages of **model construction**. Applications to yearly hydrological and other kinds of time series explain how this is executed in practice. The basic model building methods of Part III are simply extended for use with more complicated time series models given later in the book. Using practical applications, **Part IV** explains how the nonseasonal models of Part II can be used for **forecasting and simulation**. Forecasting and simulating with other models in this book simply involve making appropriate changes and extensions to the procedures given in Part IV.

The **Hurst Phenomenon** defined in Chapter 10 of **Part V** caused one of the most interesting and controversial debates ever to take place in hydrology. Both theoretical and empirical research related to the Hurst phenomenon are described in detail and a proper explanation for the Hurst phenomenon is put forward. One spinoff from research related to Hurst's work was the development of **long memory models** for which the theoretical autocorrelation function dies off slowly and is not summable (see Section 2.5.3 for a definition of long memory). The two types of long memory models presented in Part V are the **FGN** (Fractional Gaussian noise) model of Section 10.4 and the **FARMA** (fractional ARMA) model of Chapter 11.

The three kinds of seasonal models presented in **Part VI** are the **SARIMA** (seasonal ARIMA), **deseasonalized**, and **periodic models**. The latter two seasonal models are especially well designed for use with environmental time series in which certain kinds of stationarity are present in each season. Forecasting experiments demonstrate that **PAR** (periodic autoregressive) models provide better forecasts than their competitors when forecasting certain kinds of seasonal hydrological time series.

A major emphasis of this book is the use of time series models and other related statistical approaches in **environmental impact assessment** studies. Parts VII, VIII and X provide significant contributions to this topic. The type of **multiple input-single output model** presented in **Part VII** is the **TFN** (transfer function-noise) **model** which is designed for modelling situations qualitatively written as:

Single **Output** **Variable**	=	**Multiple** **Inputs**	+	**Noise**

In the above expression, for example, the single output variable may be riverflows which are caused by the input variables consisting of precipitation and temperature, plus an ARMA noise term. The type of basic structure contained in the TFN model reflects the physical realities present in many natural systems. Indeed, forecasting experiments described in Chapter 18 demonstrate that a TFN model provides more accurate forecasts than those obtained from a costly and complicated conceptual model.

The **intervention model** of **Part VIII** constitutes a worthwhile extension of the TFN model of Part VII. In addition to handling **multiple inputs** and **autocorrelated noise**, the intervention model has components for modelling the **effects of external interventions** upon the mean level of the output series and also for **estimating missing values**. The qualitative expression for the intervention model shown earlier in the Preface demonstrates the flexible design of the model. Indeed, extensive applications to both water quality and quantity data in Chapters 19 and 22 clearly show the great import of this model in **environmental impact assessment**.

Within **Part IX**, the class of **multiple input-multiple output models** that is described is the **multivariate ARMA** family of models. In order to reduce the number of model parameters, a special case of the multivariate ARMA models, which is called the **CARMA** (contemporaneous ARMA) set of models, is suggested for use in practical applications. Qualitatively, a multivariate ARMA model is written as:

Multiple Outputs	=	**Multiple Inputs**	+	**Noise**

This type of model is needed when there is **feedback** in the system. For instance, there can be feedback between water levels in a large lake and precipitation. Evaporation from the lake causes clouds to form and precipitation to take place. The precipitation in turn causes the lake level to rise from precipitation falling directly on the lake as well as increased riverflows into the lake from rivers affected by the precipitation.

In **Part X**, general methodologies and specific techniques are presented for **assessing trends** and other statistical characteristics that may be present in **messy environmental data**. Water quality time series, for instance, are often quite messy because there are a large number of missing observations and many outliers. To extract an optimal amount of information from messy environmental data, it is recommended to carry out both exploratory data analysis and confirmatory data analysis studies. Simple graphical methods can be used as **exploratory data analysis** tools for discovering the main statistical characteristics of the series under study. At the **confirmatory data analysis** stage, statistical models can be used to model formally the time series in order to confirm presence of the key statistical properties. After estimating missing data points, the **intervention model** is employed in Chapter 22 for modelling trends in water quality series measured in creeks that may have been influenced by cutting down a forest. Because there are a great number of missing observations for water quality variables measured in a large lake, **nonparametric trend tests** are employed in Chapter 23 for detecting any trends caused by industrialization near the lake. Finally, in Chapter 24, a general methodology is presented for detecting and analyzing trends in water quality series measured in rivers. A **robust locally weighted regression smooth** can be employed for visualizing the trend in a graph of the data. Furthermore, a flexible nonparametric trend test is used for confirming the presence of the trend. **Table 1.6.4** summarizes the **trend analysis approaches** used in the book within the overall framework of exploratory and confirmatory data analyses.

Most chapters in the book contain the following main components:

Descriptions of techniques
Representative applications
Appendices
Problems
References

Additionally, time series models presented later in the book usually constitute appropriate **expansions of the ARMA-type models** presented earlier. Finally, **flexible model construction methods** are presented for all of the classes of time series models described in the book. Consequently, the time series models are **completely operational** and can be used now within a systematic data analysis study.

Except for the long memory FGN model of Chapter 10, all of the time series models discussed in detail in this book are directly related to the basic ARMA model. Hence, the nonseasonal ARMA and ARIMA, long memory FARMA, three types of seasonal, TFN, intervention, and multivariate models of Parts II, V, VI, VII, VIII, and IX, respectively, all can be considered as belonging to the **extended family of ARMA models**. All of these models possess sound theoretical designs and can be conveniently applied to actual data sets using the flexible model building procedures described in the book. Furthermore, numerous practical applications and comparisons to other kinds of models clearly demonstrate the usefulness of these models in environmetrics.

Consider first the utility of the **intervention model** of Part VIII. As shown by the many applications in Part VIII and Chapter 22 of the intervention model to water quantity and quality time series, the intervention model works very well in practical applications. In fact it is probably the most useful and comprehensive time series model available for use in environmental impact assessment studies at the present time.

As summarized in **Table 1.6.3**, experimental results are provided at various locations in the book for a range of situations in which ARMA models are used for forecasting and simulation. When forecasting annual geophysical time series, **forecasting experiments** demonstrate that ARMA models and a nonparametric regression model produce more accurate forecasts than their competitors (see Section 8.3). For the case of average monthly riverflows, PAR models identified using proper identification plots provide accurate forecasts (Sections 15.3 and 15.4). As explained in Section 15.5, **combining forecasts** from different models can produce more accurate forecasts when the individual models are quite different in design and both models produce reasonably accurate forecasts. However, because SARIMA models do not forecast seasonal riverflow data nearly as well as PAR models, combining forecasts across these two models produces forecasts that are less accurate than the PAR forecasts on their own. Forecasting experiments in Chapter 18, demonstrate that a **TFN model forecasts riverflows significantly better than a conceptual hydrological model.**

Another major finding in the book is that ARMA-type models work remarkably well for **simulating** both nonseasonal and seasonal hydrological time series (see **Table 1.6.3**). As demonstrated by the **simulation experiments** outlined in Section 10.5, ARMA models statistically preserve the Hurst statistics and thereby provide a clear answer to the riddle of the Hurst phenomenon. Furthermore, as pointed out in Section 14.8, PAR models statistically preserve the critical period statistics for monthly riverflow time series.

When developing a time series model for describing a given time series, experience has shown that better models can be developed by following the identification, estimation and diagnostic check stages of **model construction**. Only a properly designed and calibrated model has the potential to work well in simulation and forecasting.

The **McLeod-Hipel Time Series (MHTS) Package** constitutes a flexible **decision support system** for carrying out comprehensive data analysis studies in order to obtain meaningful statistical results upon which wise decisions can be made. As explained in Section 1.7, the MHTS package can be used for fitting virtually all of the models presented in this book to sets of time series by following the three stages of **model construction**. The MHTS package can then utilize calibrated models for performing applications such as **forecasting and simulation** experiments. Moreover, the MH package is especially useful for executing **statistical environmental impact assessment** studies where a practitioner may use tools such as graphical methods, nonparametric trend tests, intervention models, and regression analysis. Part X of the book explains how these kinds of methods can be employed for retrieving useful information from **messy environmental data**.

As a closing to the Preface, the authors would like to comment upon the **future of environmetrics, in general, and time series modelling, in particular.** As world populations continue to expand, the demand for potable water as well as other natural resources will no doubt greatly increase. Certainly, more and more of the natural environment will be altered due to increased industrialization, expansion of agricultural lands and other land use changes. These man-induced activities could in turn cause a dramatic deterioration of the environment. To better understand how man's activities affect the environment, **extensive measurements** will have to be taken of a wide range of variables including water quality, water quantity and meteorological phenomena. Of course, proper **experimental design** procedures should be used for deciding upon where and when the data should be optimally collected. This vast array of observations will have to be efficiently stored in a complex **computer system** for subsequent use in **data analysis** and **decision making**. A wide range of **time series models**, including those described in this book, as well as other appropriate statistical methods, will be needed as key modelling techniques in the **scientific data analysis** studies of the huge amounts of environmental information. By properly collecting and analyzing the data, **better decisions** can be made for obtaining solutions to pressing environmental problems which minimize man's detrimental impacts upon the natural environment. Paradoxically, the future health of the environment is questionable while the futures of environmetrics and also time series modelling are indeed very promising. Certainly, environmetrics provides one of the "medicines" that can be used to help "cure" a sick patient who appears to be lapsing into a terminal illness. **The authors sincerely hope that their timely book on time series modelling of water resources and environmental systems will help to influence people for developing and adopting sound environmental policies.**

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