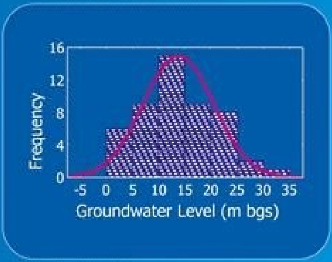
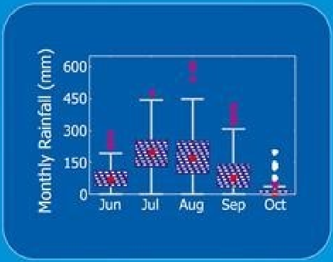
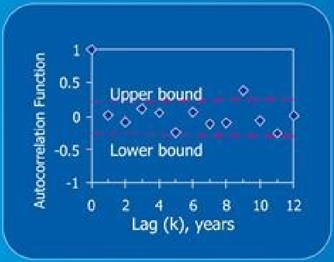
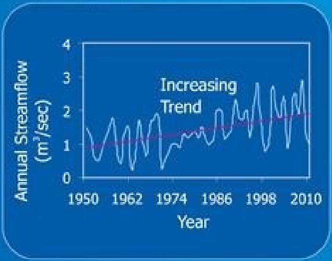
Hydrologic Time Series Analysis:
Theory and Practice

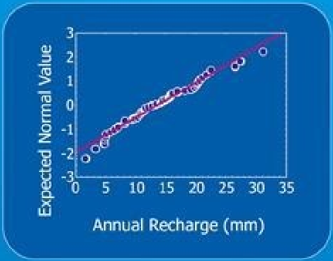
By
Deepesh Machiwal
Madan Kumar Jha

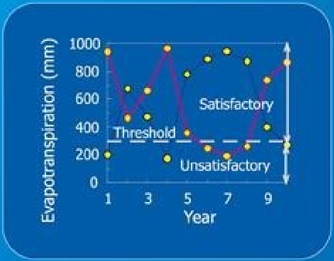












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By

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Preface

In the 21^{st} century, the entire world is suffering from freshwater scarcity due to the ever-increasing water demand in different sectors, worldwide population growth and increasing pollution of vital freshwater resources. Therefore, efficient planning and management of water resources is of utmost importance to ensure sustainable development on the earth. Statistical analyses of hydrologic time series play a central role in the planning and management of water resources. In fact, statistical analyses of every hydrologic time series must always be carried out for determining fundamental time series characteristics, i.e. normality, homogeneity, stationarity, presence of trends and shifts, periodicity, persistence and stochastic component. However, such a practice is currently missing among the hydrologists and hydrogeologists. As a result, hydrologic time series analysis has received less attention even in the era of information technology, especially in developing countries. A comprehensive review of literature by the authors revealed that the past studies on time series analysis mostly focus on a specific time series characteristic only and that the current application domain of time series is limited. Based on the research experience of the authors, it was found that a suitable book dealing with both theory and application of time series analysis techniques is lacking, particularly in the field of water resources engineering. Therefore, many hydrologists and hydrogeologists face difficulties in adopting time series analysis as one of the tools for their research. Thus, there is a need to have a book with a proper blend of theoretical and practical aspects of time series analysis, and its use in the field of water resources engineering.

The present book is an attempt to fill the above gap by providing adequate theoretical background as well as practical applications of various tools/ techniques for analyzing time series data. This book is divided into two parts: Part I describes theoretical aspects of tools/techniques available for time series analysis, and Part II presents applications of various time series tests through selected case studies. Chapter 1 deals with an overview of water problems and challenges, fundamentals of time series analysis, and the significance of time series analysis in hydrology. Chapters 2 to 6 constitute Part I, which present an overview of time series characteristics in hydrology/water resources engineering, statistical measures for summarizing time series data and evaluating system performance, methods for checking the normality of time series data, theoretical details of 31 available statistical tests along with detailed procedures for applying them to real-world time series data, theory and methodology of stochastic modelling, and current status of time series analysis in hydrological sciences. Chapters 7 to 12 constitute Part II, which demonstrate the application of most time series tests through a case study in India (authors' own work) and present a comparative evaluation of various time series tests (also authors' own work). In addition, four invited case studies are included as Chapters 9, 10, 11 and 12 from India and abroad (USA, Canada and South Africa). The contributors of the invited case studies were chosen based on their proven knowledge in the specific area of their contribution and these chapters were meticulously reviewed and edited by the authors. Thus, Chapters 9, 10, 11 and 12 have been revised at least twice.

This book will not only serve as a textbook for the students and teachers of water resources engineering field but will also solve the purpose of reference book to educate researchers/scientists about the theory and practice of time series analyses in hydrological sciences. This book will be very useful to a wide range of students, researchers, teachers and professionals such as undergraduate and postgraduate students, teachers and researchers of civil, environmental, agricultural and ecological engineering fields as well as to the practising hydrologists and hydrogeologists.

Deepesh Machiwal
Madan Kumar Jha

About the Authors

Deepesh Machiwal obtained his Bachelor of Engineering from Rajasthan Agricultural University, Bikaner, India in 1999, and Master of Engineering from Maharana Pratap University of Agriculture and Technology (MPUAT), Udaipur, Rajasthan, India in 2001. He obtained his PhD. from Indian Institute of Technology (IIT) Kharagpur, West Bengal, India in 2009. Between June 2001 and October 2001 he worked in the capacity of Senior Research Fellow in Department of Soil and Water Engineering, College of Technology and Engineering (CTAE), MPUAT. Between November 2001 and June 2005 he served as a Senior Research Fellow in Department of Agricultural & Food Engineering, IIT Kharagpur. He served from July 2005 to January 2011 as an Assistant Professor in Department of Soil and Water Engineering, CTAE, MPUAT, Udaipur, India. In February 2011, he joined as Senior Scientist in one Regional Research Station of Central Arid Zone Research Institute, situated at Bhuj, India. Dr. Machiwal has to his credit 10 publications in international refereed journals and six publications in national refereed journals, two technical reports and 17 publications in conference proceedings. He has also contributed four book chapters. He is a reviewer of national journal and international journals related to water resources engineering. He is also a life member of eight national professional societies or associations.

Madan Kumar Jha is Professor of Groundwater Hydrology at the Department of Agricultural & Food Engineering, Indian Institute of Technology (IIT) Kharagpur, West Bengal, India. He obtained his Bachelor in Technology (B.Tech., Agril. Engineering) from Rajendra Agricultural University, Bihar, India in 1990 and was the recipient of 'University Gold Medal' for outstanding academic performance. He obtained his M.Eng. from Asian Institute of Technology, Bangkok in 1992 availing full postgraduate scholarship, and PhD. from Ehime University, Japan in 1996 availing Monbusho Scholarship. Before joining IIT Kharagpur in 1999, Prof. Jha also worked as Water Resources Engineer at Panya Consultants Co. Ltd., Bangkok and as Postdoctoral Fellow at Kochi University, Japan availing 'JSPS Research Fellowship'. He has authored/co-authored three books and has contributed nine book chapters. To date, he has to his credit 50 publications in international refereed journals and six publications in national refereed journals, six technical reports and more than 60 publications in conference proceedings. He is serving as 'Assistant Managing Editor' of *Journal of Spatial Hydrology*, USA since January 2010; 'Editor' of *Journal of Water Resource and Protection*, USA since September 2010; 'Associate Editor' of *International Agricultural Engineering Journal,* China since July 2008; 'Associate Editor' of *Journal of Agricultural Engineering,* India since 2010 and 'Editor' of *Research Journal of Chemistry and Environment*, India since 2004. He is also serving as a reviewer of several international journals of water resources engineering field. He has been awarded 'Fellow' of the Institution of Engineers India (IEI), Kolkata in July 2011 as well as 'Fellow' of the Indian Water Resources Society, Roorkee in July 2008. In addition, Prof. Jha has to his credit salient scholastic awards and international fellowships, including international 'AMA-Shin-Norinsha-AAAE Young Researcher Award' by the Asian Association for Agricultural Engineering, Bangkok in 2005; 'Distinguished Services Award' in the field of Soil and Water Engineering by the Indian Society of Agricultural Engineers, New Delhi in 2002; 'JSPS Research Fellowship' (1997-1999); 'Alexander von Humboldt Fellowship' (2004-2005); and 'JSPS Invitation Fellowship (Long-Term)' in 2009. Prof. Jha is a regular or life member of several international and national professional societies/associations.

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The completion of a book with a proper blending of theoretical and practical aspects of time series analysis, and its use in water resources engineering certainly involves help and support from others besides authors' own exertion. This book is a part of constant efforts of the two authors, who extensively explored literature and did research on the application of time series analysis in hydrology and climatology for last several years. This book includes four invited case studies and the authors are grateful to the contributors who accepted our invitation gladly and extended full cooperation during revision of the manuscripts according to our detailed comments and suggestions. Each chapter has been meticulously revised at least twice. Chapters 2, 3, 4 and 5 have been greatly benefitted from Helsel and Hirsch (2002), Loucks and van Beek (2005), USEPA (2006) and Shahin et al. (1993), which is gratefully acknowledged. We also offer our gratitude to other individuals who helped indirectly in the preparation of this book.

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Finally, the first author (Deepesh Machiwal) would be failing in his duties if he does not record special thanks to his parents, wife Savita and daughter Mahi who have been a constant source of encouragement during the entire course of this hard task. The second author (Madan Kumar Jha) is especially grateful to his wife Manisha and son Piyush for their constant love, forbearance and encouragement, and sincere support during the writing of this book.

Contents

Part I: Tools/Techniques for Time Series Analysis

Part II: Salient Case Studies

1

Introduction

1.1 Water Problems and Challenges: An Overview

Water is the most precious resource of the earth because no life is possible without water. It is essential for the survival and livelihood of every human. It also regulates ecosystems, grows our food and powers our industry. Hardly any economic activity can be sustained without water. Undoubtedly, water plays a vital role in our life. Different dimensions of water functions in society and nature are (Falkenmark and Rockstrom, 2004): (i) water as *life-support* and hence as a basic need and as a human and animal right; (ii) water as an *economic* commodity in some uses; (iii) water as an *integral part of ecosystem* (sustaining it and being sustained by it); (iv) water as a *sacred resource*; and (v) water as *an inevitable component of cultures and civilizations*. Thus, water is the key resource for the human/animal health, socio-economic development, and the survival of earth's ecosystems. On the other hand, natural ecosystems also play a crucial role in the availability and quality of water through their purifying and regulating services, thereby sustaining human development on the earth. In other words, water has social, economic and environmental values and is essential for sustainable development (Falkenmark and Rockstrom, 2004; UNESCO, 2003, 2009). In contrast with many other vital resources of the earth, there is no substitute for water in most activities and processes where it is needed!

At present, about 10% of the world's freshwater supplies are used for maintaining health and sanitation, whereas agriculture accounts for about 70% and industries about 20% of the world's freshwater supplies (Shiklomanov, 1997; Shiklomanov and Rodda, 2003). Food production is the most water-intensive sector. It has been estimated that about one litre of liquid water gets converted to water vapour to produce one calorie of food. Every person is responsible for consuming 2000 to 5000 litres of water every day depending on one's diet and the method of food production, which is far more than 2 to 5 litres we drink every day (Rodriguez and Molden, 2007). A meat-based diet requires much more water than a vegetarian diet; for example, we need about

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1000 litres of water to produce one kilogram of wheat, whereas we need about 5000 to 13,500 litres of water to produce one kilogram of meat. The demand for water is gradually increasing with growing population as well as rapid urbanization and industrialization in different parts of the world (Postel, 1998; Shiklomanov and Rodda, 2003; UNESCO, 2003, 2009; Grafton and Hussey, 2011). As a result, water demand is surpassing the available freshwater resource. On top of it, in future, more people will need more water not only for food and sanitation but also for fibre, livestock and industrial crops (bio-energy).

Unfortunately, the excessive use and continued mismanagement of freshwater resources for human development (to supply ever-increasing water demands for food, feed, fibre and fuel) have led to water shortages, increasing pollution of freshwater, loss of biodiversity, and degraded ecosystems across the world (e.g., Postel, 1998; de Villiers, 2001; Steffen et al., 2002; UNESCO, 2003; UN Water, 2007; Vörösmarty et al., 2010; Grafton and Hussey, 2011). As a result, freshwater scarcity has emerged as one of the most pressing problems in the 21st century. According to Molden (2007), one in three people at present face water shortages, around 1.2 billion people (almost one-fifth of the world's population) live in areas of '*physical water scarcity*' (i.e., where the available water resources cannot meet the demands of the population), and 500 million people are approaching this situation. Another 1.6 billion people (almost one quarter of the world's population) face '*economic water scarcity*' (i.e., where countries lack the necessary infrastructure to harness water from rivers and aquifers). Furthermore, about 2.5 billion people lack adequate sanitation, and 884 million people are without access to safe water (UNICEF and WHO, 2008). It has been estimated that half of the population of the developing world is exposed to polluted sources of water that increase disease incidence. Between 1991 and 2000, over 665,000 people died in 2557 natural disasters, of which 90% were water-related disasters and a vast majority of victims (97%) were from developing countries (IFRC, 2001).

If the present trend continues, based on the widely used Falkenmark indicator for water scarcity, nearly 1.4 billion people will experience '*chronic water scarcity*' (i.e., water supply less than 1000 m^3/capita/annum) within the first 25 years of this century, mostly in semi-arid regions of Asia, North Africa and Sub-Saharan Africa. Also, 1.8 billion people will be living in countries or regions with '*absolute water scarcity*' (i.e., water supply less than 500 m^3/capita/annum), and two thirds of the world's population could be under '*water stress*' (i.e., water supply less than 1700 m^3/capita/annum) conditions by 2025 (UN Water, 2007). Urban and industrial water use in the world is projected to double by 2050. With increasing evidence of unsustainable water use in several parts of the world, particularly in developing nations, India is under *'water stress'* conditions today and will face *'chronic water scarcity'* by 2025. The problem of water management in general and water shortages in particular will worsen in many parts of the world due to global climate change. Higher temperatures and changes in extreme weather conditions are projected to affect the availability and distribution of rainfall, snowmelt, river flows and groundwater, and deteriorate water quality, which in turn can have severe impacts on both urban and rural regions of the world (IPCC, 2007). Climate change is considered as a major challenge to the efficient management of natural resources and a barrier to the transition from poverty to prosperity (UNDP, 2007). Thus, in the beginning of the 21^{st} century, we are bound to face the stark reality that the current patterns of water development and consumption are not sustainable in several countries of the world. Therefore, there is an urgent need for widespread realization that freshwater is a finite and vulnerable resource, which must be used efficiently, equitably and in an ecologically sound manner for present and future generations to ensure sustainable development on the earth.

Inadequate water resource systems reflect failures in planning, management and decision making not only in the water sector but also in other sectors of society directly or indirectly dependent on water. It is the need of the hour for scientists/engineers as well as for planners and decision makers to efficiently plan, develop, operate and manage water resource systems so as to ensure adequate, cost-effective, good-quality and sustainable supply of water for humans and nature (Falkenmark and Rockstrom, 2004; Loucks and van Beek, 2005; Grafton and Hussey, 2011). The complex and deep interactions that have existed between humans and water systems throughout the human history need to be understood by modern scientists/engineers, planners and decision makers (Postel and Richter, 2003). It is also essential to recognize that unlike much basic economic theory, the goods and services provided by ecosystems are not at all substitutable and ecosystems cannot easily be replaced by technology (Kaufmann, 1995). At this point in human evolution, it is vital that people understand the crucial link between human welfare and ecosystem well-being (Arrow et al., 1995; UNESCO, 2003, 2009), and institutions must be strengthened to support effective water governance (Walker, 2009). Natural scientists and social scientists need to work together to better understand human-environment interactions (IPCC, 2001) as well as to bridge the growing knowledge gap between water management and ecology. More and more research is needed to predict how potential ecosystem perturbations may affect short- and long-term ecosystem functionality. Given the dynamic and evolving nature of ecosystems, a major technical challenge is quantifying how much the ability of ecosystems to meet human needs is changing over time.

Today, one of the biggest challenges is how we can effectively balance freshwater for human development and ecosystems welfare in achieving equity, environmental sustainability, and economic efficiency in the face of looming global climate change. Quantitative analysis using statistical and mathematical modelling tools as well as modern information technologies such as remote sensing, GIS, decision support system, expert system, etc. can support and improve water resources planning and management (Loucks and van Beek, 2005; Jha and Peiffer, 2006; Jha, 2010). The "think globally, act locally" slogan of the late 1980s reminds us of our professional attitudes to and scientific responsibilities for environment (nature) in general and freshwater resources in particular, which must not be forgotten. Following holistic and multidisciplinary approaches as well as using modern concepts and tools/techniques, water scientists and engineers must make sincere and sustained efforts to improve their understanding about hydrologic/hydrogeologic processes and their linkage with our ecosystems; thereby improving both the process and product. It is worth mentioning that the existing tools and technologies, irrespective of their sophistication, will not eliminate the need to reach conclusions and make decisions on the basis of incomplete and uncertain data, and scientific knowledge (Loucks and van Beek, 2005). In other words, the importance of professional judgement and that of research, development and education in the planning and management of water resources must not be undermined amidst increasing popularity and reliance on new/emerging tools and technologies in the 21st century.

1.2 What is Time Series?

The term *time series* is defined as "a sequence of values collected over time on a particular variable" (Haan, 1977). A time series can consist of the values of a variable observed at discrete times, averaged over a given time interval, or recorded continuously with time. It may consist of only deterministic events, only stochastic events, or a combination of deterministic and stochastic events. Generally, a hydrologic time series is composed of a stochastic component superimposed on a deterministic component (Haan, 1977; Shahin et al., 1993). The deterministic component can be classified as a trend, a jump, a periodic component, or a combination of these (Haan, 1977). The time intervals for most hydrologic time series are hour, day, week, month, season or year. Data in business, economics, engineering, environment, medicine, earth sciences, hydrology, climatology, meteorology and other areas are often collected in the form of time series. Some examples of the general time series are share prices on successive days, company profits in successive years, and sales figures in successive weeks/months/years; while the examples of hydrologic time series are hourly/daily/monthly/annual temperature (air or water) readings, precipitation in successive days/weeks/months/years, hourly/daily/monthly/annual evaporation or evapotranspiration readings, hourly/daily/monthly/annual soil moisture, hourly/daily/weekly/monthly/annual streamflow or river-stage readings, hourly/daily/weekly/monthly/annual groundwater-level readings, hourly/daily/weekly/monthly/annual tide-level readings, daily water consumption in domestic, industrial or agricultural sectors, etc.

Furthermore, the *realization* of a process is the outcome of an experiment in which the process is observed, and hence a single time series is known as a *realization* (Shahin et al., 1993). The term *ensemble* denotes a collection of all possible realizations of a process, and it is used in the theory of stochastic processes and time series analysis in lieu of the well-known statistical term ‘population’ (Haan, 1977; Shahin et al., 1993). The properties of a time series can be obtained based on a single realization over a time interval or based on several realizations at a given time. The properties based on a single realization are known as *time average properties*, whereas those based on several realizations at a particular time are known as *ensemble properties* (Haan, 1977). If the *time average properties* and the *ensemble properties* of a time series are same, the series is said to be *ergodic* (Haan, 1977). *Ergodicity* is the property by which each realization of a given process is a complete and independent representative of all possible realizations of the process (Shahin et al., 1993). Thus, the *ergodicity* allows the scientists/researchers to determine the statistical properties of a process from a single realization.

1.3 Time Series Analysis

Time series analysis is the investigation of a temporally distributed sequence of data or the synthesis of a model for prediction wherein time is an independent variable. Sometimes, time is not actually used to predict the magnitude of a random variable such as peak runoff rate, but the data are ordered by time. The main intent of time series analysis is to detect and describe quantitatively each of the generating processes underlying a given sequence of observations (Shahin et al., 1993). Hydrologic time series are analyzed for several reasons. The main reason as reported in the literature is to detect a trend due to another random hydrologic variable. Secondly, time series may be analyzed to develop and calibrate a model that would describe the time-dependent characteristics of a hydrologic variable. Thirdly, time series models may be used to predict future values of a time-dependent variable. Besides the time-dependent data series, there are space-dependent data series of hydrologic systems, which are known as ‘spatial data series’. Thus, in the spatial data series, the data are location specific instead of depending on time as in the time series. The examples of spatial data series are: the variability of groundwater levels over a groundwater basin, spatial variation of aquifer or soil properties, spatial variation of rainfall in a catchment/basin, and so on. Most of the time series analysis methods can equally be applied to spatial data series (Shahin et al., 1993). Therefore, spatial data series is sometimes referred to as time series.

There are four major steps involved in a time series analysis (McCuen, 2003): (i) detection, (ii) analysis, (iii) synthesis, and (iv) verification. In the detection step, systematic components of the time series such as trends or periodicity are identified. It is also necessary to decide in this step whether the systematic effects are physically and statistically significant. In the analysis step, the systematic components are analyzed to identify their characteristics including magnitudes, form and their duration over which the effects exist. In the synthesis step, information from the analysis step is accumulated to develop a time series model and to evaluate goodness-of-fit of the developed model. Finally, in the verification step, the developed time series model is evaluated using independent sets of data. For further details of the time series analysis, the readers are referred to the specialized books on time series analysis such as Yevjevich (1972), Salas et al. (1980), Bras and Rodriguez-Iturbe (1985), Cryer (1986), and Clarke (1998).

1.4 Classification of Time Series

A time series can be classified in many ways according to different criteria. Three widely used classifications of the time series are described below. The details about the classification of hydrologic time series can be found in Salas (1993).

1.4.1 Discrete or Continuous Time Series

Time series can be either continuous or discrete. A time series is called 'discrete' if the observations are recorded at different time instants or at different points in space (Haan, 1977; Shahin et al., 1993). On the other hand, if the observations are recorded continuously in time or space, then the series is known as a 'continuous time series'. 'Discrete time series' is often derived from a 'continuous time series'. Usually in hydrology, a time series is of the discrete type. As a result, the case studies presented in this book are restricted to the discrete time series. A continuous plot of a 'discrete time series' should not be confused with a 'continuous time series'.

1.4.2 Full or Partial Duration Series

A 'full time series' is the one which contains all the recorded observations over time or space (Haan, 1977; Shahin et al., 1993). As the name suggests, a 'partial duration series' contains only selected observations which are extracted from the full time series. For instance, daily rainfall recorded at a specific location over a given period of time constitutes a full time series of rainfall. A time series of one-day maximum rainfall can be extracted from the full rainfall time series by arranging the maximum rainfall occurring in a day for each year in the order of occurrence. Note that the maximum rainfall time series contains less information than the original full rainfall time series. That is, a 'partial duration series' always contains less information than the 'full time series'. In addition, the observation points in a partial duration series may not be equidistant.

1.4.3 Univariate or Multivariate

If only one variable is observed at each time, the time series is known as 'univariate time series'. However, if two variables are observed at the same time (simultaneously), the series is known as 'bivariate time series'. If more than two variables are observed simultaneously at a time, the series is known as a ‘multivariate time series’. This book deals with univariate time series only.

1.5 Structure of Time Series

A time series is often adequately described as a function of four components: *trend*, *seasonality*, *dependent stochastic component* and *independent residual component*. In general, a time series can be mathematically expressed as (Shahin et al., 1993):

$$x_t = T_t + S_t + \varepsilon_t + \eta_t \tag{1}$$

where T_t = trend component, S_t = seasonality, ε_t = dependent stochastic component, and η_t = independent residual component.

In the time series analysis, it is assumed that the data (observations) consist of a *systematic pattern* and *random noise* (error); the latter usually makes the pattern difficult to be identified. The *systematic pattern* is represented by the first two components of Eqn. (1), which are deterministic in nature, whereas the stochastic component accounts for the random error. Generally, the stochastic component contains a dependent part which may be represented by an ARMA(p,q) model, where ‘p’ and ‘q’ are the orders of the autoregressive and moving-average models, respectively, and an independent part that can only be described by some sort of probability distribution function. When $p = 0$, the ARMA(p,q) represents an MA(q) model, and when $q = 0$, it represents an AR(p) model.

Thus, the process of hydrologic time series analysis should be viewed as a process of identifying and separating the total variation in measured data into above-mentioned four components. When a time series has been analyzed and the components accurately characterized, each component can then be modelled. Methods for identifying trends in time series are described in Chapter 4 and the methods for identifying stochastic component are described in Chapter 5.

1.6 Salient Characteristics of Time Series

Most statistical analyses of hydrologic time series at the usual time scale encountered in water resources studies are based on a set of fundamental assumptions, which are: the series is homogenous, stationary, free from trends and shifts, non-periodic with no persistence (Adeloye and Montaseri, 2002). The term ‘homogeneity’ implies that the data in the series belong to one population, and therefore have a time invariant mean. Non-homogeneity arises due to changes in the method of data collection and/or the environment in which it is done (Fernando and Jayawardena, 1994). On the other hand, ‘stationarity’ implies that the statistical parameters of the series computed from different samples do not change except due to sampling variations. A time series is said to be *strictly stationary* if its statistical properties do not vary with changes of time origin. A less strict type of stationarity, called *weak stationarity* or *second-order stationarity*, is that in which the first- and second-order moments depend only on time differences (Chen and Rao, 2002). In nature, *strictly stationary* time series does not exist, and *weakly stationary* time series is practically considered as stationary time series.

There are many ways by which changes in the hydro-meteorological series can take place. A change can occur gradually (known as 'trend') or abruptly (known as 'step change' or 'jump'), or may take more complex form (Shahin et al., 1993). A 'trend' is defined as "a unidirectional and gradual change (falling or rising) in the mean value of a variable" (Shahin et al., 1993). A time series is said to have trends, if there is a significant correlation (positive or negative) between the observed values and time. Trends and shifts in a hydrologic time series are usually introduced due to gradual natural or human-induced changes in the hydrologic environment producing the time series (Haan, 1977; Salas, 1993). Gradual or natural changes in hydrologic variables could be caused by a global or regional climate change, which would be a representative of changes occurring over the study area. Changes in the observed variables that may not be able to be extrapolated over a study area could be caused by a gradual urbanization of the area surrounding the monitoring site, changes in the method of measurement at the monitoring site, or by moving the monitoring site even a short distance away. 'Step changes' or 'jumps' in a time series usually result from catastrophic natural events such as earthquakes, tsunami, cyclones, or large forest fires which quickly and considerably alter the hydrologic regime of an area. The man-made changes such as the closure of a new dam, the beginning or termination of groundwater pumping, or other such developmental activities may also cause jumps in some hydrologic time series (Haan, 1977). Jumps can be either positive or negative. The 'jump' or 'step change' is usually noted in the overall record at a monitoring site, but this information is not always presented with the site's data series. Thus, the variables that appear to have a trend may actually just represent a change in climatological or hydrological conditions near the monitoring site. Under such conditions, the affected climatological data should be modified so that the values are better representative of the study area as a whole (Hameed et al., 1997). A key element in this process is the ability to demonstrate whether a change or trend is present in the climatological data series and to quantify this trend, if it is present.

'Periodicity' is another characteristic of time series (natural hydrologic time series), which represents a regular or oscillatory form of movement that is recurring over a fixed interval of time (Shahin et al., 1993). It generally occurs due to astronomic cycles such as earth's rotation around the sun (Haan, 1977; Kite, 1989). Annual cycles are often apparent in rainfall, evapotranspiration, streamflow, groundwater level, soil moisture and other types of hydrologic data (Haan, 1977). Weekly cycles may be present in the water-use data of domestic, industrial, or agricultural sectors; many times the water-use time series contain both annual and weekly periodicities (Haan, 1977). In order to identify and quantify the periodicity in a hydrologic or climatologic time series, the time scale should be considered less than a year (i.e., month or six-month). The periodicity effect is not discernible in an annual time series, and hence half-annual or monthly time series normally encountered in hydrology can be used for analyzing the periodicity.

Lastly, the phenomenon of 'persistence' is highly relevant to the hydrologic time series, which means that the successive members of a time series are linked in some dependent manner (Shahin et al., 1993). In other words, 'persistence' denotes the tendency for the magnitude of an event to be dependent on the magnitude of previous event(s), i.e., a memory effect. For example, the tendency for low streamflows to follow low streamflows and that for high streamflows to follow high streamflows. Thus, 'persistence' can be considered synonymous with autocorrelation (O'Connel, 1977). Hurst (1951, 1957) was the first person to describe 'persistence' comprehensively in his studies on a reservoir design across the Nile River. The phenomenon was defined in terms of a parameter called "Hurst's coefficient", the average value of which is approximately 0.73 for very large samples. However, its theoretical value for an independent Gaussian process to which hydrologic series are assimilated should be 0.5 (Capodaglio and Moisello, 1990). If the theoretical and the observed values of Hurst's coefficient do not correspond, it is known as "Hurst's phenomenon". All the stochastic models that have been proposed to represent hydrologic time series have attempted to include the persistence phenomenon. However, with the time series records commonly available in hydrology, it is virtually impossible to identify any long-term persistence in the hydrologic time series (Capodaglio and Moisello, 1990). Chapter 4 deals with various methods/tests used for identifying the above characteristics of a time series.

1.7 Time Series Analysis vis-a-vis Hydrology

In early days, the application of statistics in hydrology was restricted to only surface water problems, especially for analyzing the hydrologic extremes such as floods and droughts. However, during the past three decades or so, the application of statistics in hydrology has expanded considerably to encompass the problems of both surface water and groundwater systems, including atmospheric systems. With such a broad domain coupled with the rapid advancement in computer and data management technologies, statistics has emerged as a powerful tool for analyzing hydrologic problems. Particularly, time series analysis has become a major tool in hydrology in the era of information technology. Today, besides the basic statistical analysis of hydrologic time series, the applications of time series analysis in hydrological sciences include development of mathematical models to generate synthetic hydrologic data, to forecast hydrologic events, to identify trends and shifts in hydrologic data, to fill in missing observations, and to extend short hydrologic records (Salas, 1993). Certainly, time series analysis has become a vital tool in hydrological sciences and its importance has dramatically enhanced in the recent past due to ever-increasing interest in the scientific understanding of climate change.

In epilogue, statistics is just one of the several tools available for application in hydrological sciences. Like other tools and techniques of hydrology/water resources engineering, statistical models and methods can serve as valuable tools in the analysis and solution of several real-world water problems. It should be noted that the usefulness of any tool or technique, and hence the reliability of a hydrologic analysis/estimate depends squarely on the proficiency and knowledge of the hydrologists/water resources engineers. Unfortunately, the time and energy associated with the development of a model and the complexity involved in modelling or analysis often so focus the modellers, especially novice modellers, that they believe that the model is indeed a full representation of reality/natural systems. However, in reality, no model whether statistical or mathematical or some combination of the two can describe the actual and complete hydrology of any natural system (Haan, 2002); it is always simpler than the prototype/natural system. We should never forget that a model is a simplified form of reality and that it is simply a tool to assist in decision making, not a replacement for it! No models or techniques, no matter how complex they are, can replace the vital role of hydrologists' competency and their in-depth knowledge of water systems in making efficient decisions for solving water problems.

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PART I

Tools/Techniques for Time Series Analysis