

## Applied Hydrology

This comprehensive textbook combines the theoretical principles of engineering hydrology together with their practical applications, using modern industry-standard software. The textbook is written by the combination of a practitioner of water resources engineering with over 30 years of professional experience and a highly respected academic and recognized world authority in hydrology. Examples are drawn from global case studies, with exercises available online. The book begins with a review of the necessary mathematics and statistical hydrology. The underlying principles of the geographic information systems are discussed. In addition to topics covering fundamental concepts, separate chapters are devoted to reservoir operations, water resources management, climate change, and various methods of optimizing hydrologic models for calibration and validation. This textbook will prove to be indispensable for advanced students in civil, environmental, and agricultural engineering, preparing them to confidently join the industrial sector. It will also be an indispensable reference textbook for practicing engineers, bringing them up to date with modern techniques in applied hydrology.

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“The book *Applied Hydrology* by Biswajit Mukhopadhyay and Vijay Singh is a very comprehensive handbook on hydrologic methods. Dr. Mukhopadhyay and Dr. Singh have created a book which is one of the most thorough and in-depth coverages of a wide range of hydrologic methods and topics. Not only is this book a great reference, but it is also an excellent how-to for hydrologists across the US and many other countries.”

Jerry L. Cotter, Chief of Water Resources,  
US Army Corps of Engineers, Fort Worth District

“Altogether different from many other books which address hydrology: this book addresses all essential theories and methods of applied hydrology in detail, and at the same time seamlessly integrates the principles with practice using the current industry standard software. All examples given in the book are drawn from real-world cases based on the first author’s rich experience in working on engineering hydrology for over three decades in various corners of the globe. In addition to the fundamental concepts, the book delves deep into many contemporaneous topics such as climate change, reservoir operations, and model optimization techniques. The book is suitable both for an advanced course in applied hydrology at a university and as a companion for practicing civil, environmental, and agricultural engineers.”

Ataul Hannan, Director, Planning Division, Harris County Flood Control District

“*Applied Hydrology* is a well-written textbook that provides an in-depth treatment of the principles of applied hydrology, with excellent illustrations, examples, exercises, and numerous references. This book will serve students – both graduate and undergraduate – as well as practicing professionals, and is a valuable reference for the members of the research community.”

Venkataraman Lakshmi, University of Virginia;  
President-Elect, Hydrology Section, American Geophysical Union

“*Applied Hydrology* by Mukhopadhyay and Singh provides an advanced quantitative and mathematical treatment of estimation problems that hydrologists have to deal with. The choice of material is thoughtful and comprehensive, emphasizing both conceptual understanding and problem-solving skills. The book will help prepare both undergraduate and graduate students for the problems they will face in practice.”

Murugesu Sivapalan, University of Illinois at Urbana–Champaign

“The book *Applied Hydrology* by Mukhopadhyay and Singh provides a clear in-depth presentation of the full range of topics encountered in the professional practice of hydrologic engineering, supported by relevant articulations of foundational principles of mathematics, statistics, and hydrologic science.”

Ralph A. Wurbs, Texas A&M University

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To the women of my life

Mitsu (Shyamosree Mukhopadhyay)

and

Chini (Anosua Senesac-Mukhopadhyay)

*BM*

To wife Anita (who is no more), son Vinay, daughter Arti, daughter-in-law Sonali,  
son-in-law Vamsi, and grandchildren Ronin, Kayden, Devin, and Alivia

*VPS*

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## Preface

The security of water, food, energy, and environment is essential to sustainable development, as highlighted in the 17 Sustainable Development Goals (SDGs) adopted by the United Nations, for example, ensuring water and sanitation for all (Goal 6), food security and improved nutrition (Goal 2), affordable and reliable energy (Goal 7), and combating climate change and its impacts (Goal 13). Thus, water security, food security, and energy security are amongst the key challenges of the twenty-first century compounded by growing population, rising standard of living, and climate change. Fundamental to meeting these challenges is water security, that is, without water security, food security and energy security cannot possibly be achieved. By definition, water security implies access at all times to sufficient and quality water to satisfy varied needs and is built on three pillars: (1) demand for and use of water, (2) availability and supply of water, and (3) access to water. Essential to achieving water security and to sustainable development is water resources management encompassing water supply, agricultural irrigation, land reclamation, drainage infrastructure design, and flood control measures. *However, water resources cannot be managed without hydrology.* This may partly explain that a course in hydrology is taught in most institutions in the world that offer programs in civil, agricultural, and environmental engineering, watershed management, geography, and earth sciences. Further, there is growing interest in water resources even in socio-economic departments in many universities in the United States. The hydrology course in engineering disciplines is aimed at applications to planning, development, design, and management, and other applied aspects, that is, the course essentially is **applied hydrology**. On the other hand, the hydrology course in science disciplines is more process-oriented and has fringes of engineering applications.

There are several excellent books on hydrology some of which are standard textbooks. However, none of these books focuses on the **contemporaneous standards** of practices for practicing engineers whose work primarily revolves around stormwater management, flood risk management, supporting designs of hydraulic structures related to urban drainage systems, transportation, hydroelectricity, flood control and flood risk management, and water resources management for drinking water supplies. The term “contemporaneous standards” refers to the currently used or most widely adopted methods of computation of hydrologic variables and software applications. There is therefore a need for a standard up-to-date reference for the student preparing to enter the practice of water resources engineering and for the community of practicing hydrologic engineers for quick access to the fundamentals and exploring the areas where there are gaps in knowledge and understanding that can be filled by further research and investigation. This is what constituted the motivation for writing this book.

The subject matter of the book is divided into 21 chapters. Providing a condensed history of hydrology, Chapter 1 introduces hydrology by providing a brief discussion of hydrologic science and engineering, hydrologic system, hydrologic processes, hydrologic modeling, hydrologic models, and hydrologic data sources. The chapter is concluded with the organization and highlights of the book. Hydrologic analysis and synthesis require applications of certain mathematics, which is reviewed in Chapter 2, covering concepts of derivative and integral, differentiation and integration of standard functions, higher-order derivatives, partial derivatives, error propagation, series expansion of functions, integral transforms, convolution integrals, linear systems, linear first-order ordinary differential equations, periodic functions, Fourier series, Fourier transform, and matrix algebra. These aspects are employed in subsequent chapters.

Hydrology involves random variables and stochastic processes. Thus, Chapter 3 discusses statistical methods, covering random variables and variates, sample and population, frequency distributions, moments and moment measures, probability and stochastic processes, discrete and continuous probability distributions, return periods and quantiles, parameter estimation, hypothesis testing, confidence intervals, covariance, regression and correlation, and time-series analysis.

The key input to hydrologic modeling is rainfall which is treated in Chapter 4 dealing with rainfall measurements and models, methods of rainfall measurement, types of rainfall, rainfall statistics, spatial and temporal distributions of rainfall, design storms, frequency analysis of annual maxima and partial duration series, intensity–duration–frequency relationships, depth–area relationships, temporal distribution of design rainfall, probable maximum precipitation, gridded rainfall, and design of rain-gauge networks.

The key output of hydrologic models is streamflow whose measurements and statistics are discussed in Chapter 5, which deals with stage measurement, discharge measurement, stage–discharge relationships, streamflow statistics, flow-duration analysis, flood-frequency analysis, trends and correlation, regional frequency analysis, and environmental flow.

Fundamental to hydrologic modeling is the characterization of watershed wherein hydrologic processes occur. Chapter 6 deals with watershed geomorphology and characteristics, including hierarchical structure of a drainage basin, morphological parameters, hypsometry, stream order, Horton’s laws, stream power, longitudinal stream profile, hydraulic geometry, drainage density, drainage pattern, lag time, and time of concentration.

After presenting the essential concepts of mathematics, statistics, rainfall, streamflow, and watershed characterization, which form the foundation of applied hydrology, we proceed to present various hydrologic processes and computational methods that are at the core of hydrologic engineering practice.

All rainfall does not become runoff, for part of it is lost to abstractions, covered in Chapter 7, which discusses effective rainfall, interception, infiltration, infiltration models, effective rainfall estimation, surface storage, initial abstractions, and soil-moisture accounting.

One of the key components of the hydrologic cycle is groundwater which gives rise to baseflow. Groundwater and baseflow are thus discussed in Chapter 8 covering aquifers and their properties, gaining and losing streams, governing equations for groundwater flow, baseflow separation, baseflow models, parameter estimation, and the linear reservoir model.

One of the main methods for surface runoff modeling is the unit hydrograph method. Unit hydrograph models are presented in Chapter 9 dealing with the representation of a watershed as a linear time-invariant system, response function and convolution, unit hydrograph characteristics and derivation, synthetic unit hydrographs, instantaneous unit hydrographs and their models and parameter estimation, and the application of unit hydrographs and instantaneous unit hydrographs. One of the main physically based methods for overland flow and channel-flow modeling is the kinematic wave method. Chapter 10 discusses kinematic wave models, including kinematic wave equations for channel flow and overland flow, analytical solutions, numerical solutions, distinguishing features of kinematic wave model, and implementation of kinematic wave model in the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS).

The unit hydrograph and kinematic wave methods yield the runoff hydrograph. However, many design problems, such as urban drainage and channel sizing require only peak discharge which is often estimated by the rational method described in Chapter 11, presenting the rational method equation, the rational coefficient, drainage area, characteristic time, implications of the method, the modified rational method and its implications, and applications.

Overland flow is transported by channel flow. Chapter 12 describes channel routing, including governing equations, characteristics of flood wave movement, channel routing methods, a selection of routing methods, comparison of hydrologic and hydraulic methods of routing, and channel routing in HEC-HMS. In real world, there are dams built on rivers which impound water forming reservoirs. Thus, channel flow feeds these reservoirs and flow routing through the reservoirs needs to be modeled. Reservoir routing is discussed in

Chapter 13 dealing with storage–discharge relations, methods of routing, numerical methods of flood routing and accuracy, existing and proposed reservoirs, reservoir routing in HEC-HMS, and storage methods.

A significant part of water from reservoirs and lakes as well as from land evaporates. Likewise, a large quantity of water is evapotranspired from cropland and vegetated surfaces. Evapotranspiration is also a key component of the hydrologic cycle. Chapter 14 deals with evaporation and evapotranspiration. Beginning with a discussion of evaporation thermodynamics, it goes on to discuss factors controlling evaporation, evaporation estimation, models of evapotranspiration, selection of a method, estimation of net radiation, measurement of evaporation, potential evapotranspiration, reference and actual evapotranspiration, and estimation of actual evapotranspiration.

In cold regions, a significant part of precipitation occurs in the form of snow, which upon melting either by itself or in combination with rainfall can generate flooding. Hence, snowmelt is an important component of streamflow generation and water supply. Chapter 15 presents snowmelt, discussing energy flux, physical properties of snow, metamorphism of snowpack, rate of snowmelt, energy exchange mechanisms, turbulent convection, snowmelt runoff generation, and snow-covered areas.

Water quality is an integral part of water resource management and it is known that a large pollutant load is carried by sediment that primarily originates in the upland areas. Hence, erosion and sedimentation are discussed in Chapter 16 covering erosion process, types of erosion, estimation of erosion, sediment yield and its determination, temporal distribution of sediment yield, sediment loads in channels, sediment transport, sediment properties, fall velocity, sediment transport functions, sediment routing, reservoir sedimentation, and erosion and sedimentation modeling in HEC-HMS.

For water supply for varied purposes, water is stored in lakes and reservoirs. The reservoirs must be operated considering demand and supply and the purpose of reservoirs. Chapter 17 deals with reservoir operation, including rule curves, methods of mathematical programming, optimization of reservoir operations, simulation models, reservoir operation modeling with the HEC-ResSim software, mass curves, and reservoir siltation.

The hydrologic cycle is being impacted by climate change, which is being manifested by global warming. Therefore, hydraulic structures must be designed, and water resources must be managed considering the impact of climate change, which is the subject of Chapter 18 covering climate and hydrological processes, evapotranspiration, precipitation, snowpack, glaciers, streamflow, and urban climate change.

Chapter 19 deals with water resources management, discussing water availability, water balance, integrated water resources management, integrated river basin management, and hydrology in a changing world. For water resources management and hydrologic modeling, geographic information system (GIS) technology has become essential. This subject is therefore discussed in Chapter 20 encompassing database management, geodatabases, data structure of geographic features, topologic data structure, geographic data models, types of data models, earth datum, map projections, map scales, geoprocessing and geo-visualization, delineation of drainage areas and streams, and derivation of hydrologic parameters using GIS technology.

Finally, Chapter 21 is on hydrologic modeling, with particular focus on model calibration and applications of hydrologic models in water resources engineering. Beginning with a short discussion of hydrologic models, the chapter goes on to discuss model calibration through optimization, goodness-of-fit indices, measures of model performance, optimization methods, model validation, and sensitivity analysis. A part of the chapter is devoted to the discussion of optimization models included in HEC-HMS. The chapter is concluded with several examples of applications of hydrologic models and various physical settings of hydrologic systems.

The subject matter of the book is intended for a broad audience, including students specializing in water resources; instructors offering a course in hydrology for engineers; practitioners of hydrology dealing with real-world problems on a daily basis needing a good grounding of the subject through self-teaching by having one comprehensive text that does not contain too many materials of purely academic interest and methods or concepts that are

either obsolete or have not gained wide acceptance or popularity; and for researchers whose curiosity is driven by a desire to contribute towards solutions of problems of practical importance. Although the book focuses on engineering applications, it may be appealing to those working in agricultural, environmental, earth, ecological, and watershed sciences.

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A concerted effort has been made in this book to use data and examples from the real world. For this reason, some of the models used in various places of this book are modified or scaled-down versions of project models developed by the first author at various organizations with whom he was associated at different stages. Other models presented here he developed himself during the preparation of this book, but still drawing on data and project examples from the real-world experience gained through his association with these outstanding private-sector engineering firms.

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xviii Acknowledgments

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## Common Abbreviations

ADCP	acoustic Doppler current profiler	IDW	inverse-distance weighting
AEP	annual exceedance probability	IRF	impulse response function
AET	actual evapotranspiration	LP III	log Pearson type III
AMS	annual maximum series	MAF	moisture adjustment factor
ARF	area reduction factor	MAP	mean areal precipitation
ARI	average recurrence interval	MRM	modified rational method
CDF	cumulative probability distribution function for a <i>discrete</i> random variable	MSL	mean sea level
cdf	cumulative probability distribution function for a <i>continuous</i> random variable	MUSLE	modified universal soil loss equation
CWC	Central Water Commission (India)	NASA	National Aeronautics and Space Administration
DAD	depth–area–duration	NIH	National Institute of Hydrology (Roorkee, India)
DDF	depth–duration–frequency	NOAA	National Oceanic and Atmospheric Administration of the United States
DEM	digital elevation model	NRCS	Natural Resources Conservation Commission (under the United States Department of Agriculture)
DRH	direct runoff hydrograph	NWS	National Weather Service (United States)
EMA	expected moments algorithm	pdf	probability density function
ERH	effective rainfall hyetograph	PDF	probability distribution function
EV I	extreme value type I	PDS	partial duration series
EV III	extreme value type III	PET	potential evapotranspiration
FAO	Food and Agricultural Organization of the United Nations	PILF	potentially influential low flood
FFA	flood-frequency analysis	PMF	probable maximum flood
FHWA	Federal Highway Administration (under the United States Department of Commerce)	PMP	probable maximum precipitation
FWS	flood warning system	PMS	probable maximum storm
GEV	generalized extreme value	POR	period of record
GIS	geographic information system	PRF	pulse response function
HEC	Hydrologic Engineering Center	SCS	Soil Conservation Service (now NRCS)
HEC-	Hydrologic Engineering Center – Hydrologic	SRF	step response function
HMS	Modeling System	SRTD	synthetic rainfall time distribution
HEC-	Hydrologic Engineering Center – River Analysis	STP	storm total precipitation
RAS	System	TRMM	Tropical Rainfall Measuring Mission
HEC-	Hydrologic Engineering Center – Statistical	USACE	United States Army Corps of Engineers
SSP	Software Package	USDA	United States Department of Agriculture
HSG	hydrologic soil group	USGS	United States Geological Survey
HUC	hydrologic unit code	USLE	universal soil loss equation
IDF	intensity–duration–frequency	WMO	World Meteorological Organization