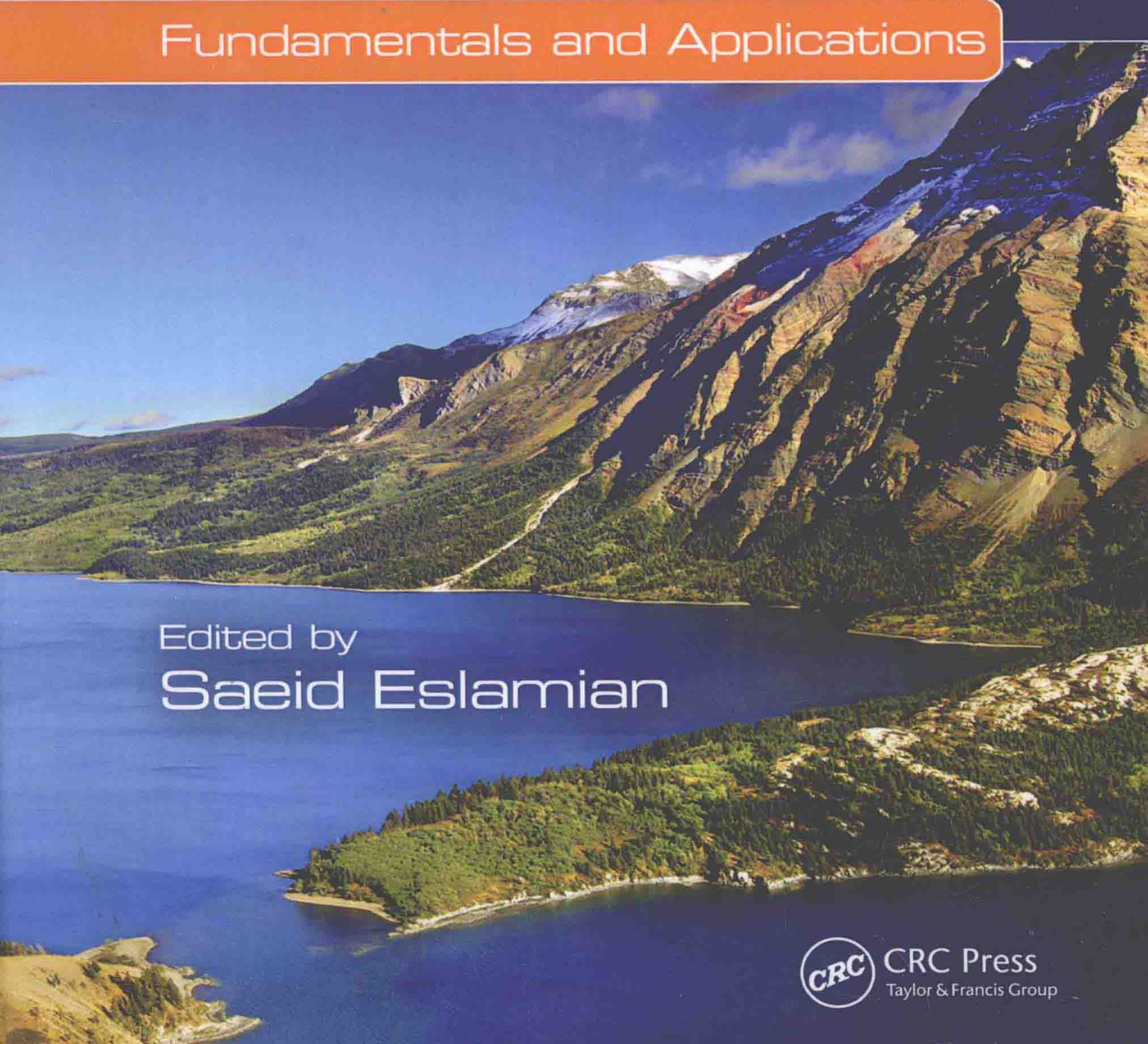
Handbook of

Engineering Hydrology

Fundamentals and Applications



Edited by
Saeid Eslamian

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Preface

Hydrological and ecological connectivity is a matter of high concern. All terrestrial and coastal ecosystems are connected with water, which includes groundwater, and there is a growing understanding that "single ecosystems" (mountain forest, hill forest, mangrove forest, freshwater swamp, peat swamp, tidal mudflat, and coral reef) that are actually the result of an artificial perception and classification can, in the long term, only be managed by a holistic vision at the watershed level. It is essential to investigate ecosystem management at the watershed level, particularly in a changing climate.

In general, there are two important approaches:

1. Adaption to hydrological events such as climate change, drought, and flood
2. Qualitative and quantitative conservation of water, thereby optimizing water consumption

The *Handbook of Engineering Hydrology* aims to fill the two-decade gap since the publication of David Maidment's *Handbook of Hydrology* in 1993 by including updated material on hydrology science and engineering. It provides an extensive coverage of hydrological engineering, science, and technology and includes novel topics that were developed in the last two decades. This handbook is not a replacement for Maidment's work, but as mentioned, it focuses on innovation and provides updated information in the field of hydrology. Therefore, it could be considered as a complementary text to Maidment's work, providing practical guidelines to the reader. Further, this book covers different aspects of hydrology using a new approach, whereas Maidment's work dealt principally with classical components of hydrologic cycle, particularly surface and groundwater and physical and chemical pollution.

The key benefits of the book are as follows: (a) it introduces various aspects of hydrological engineering, science, and technology for students pursuing different levels of studies; (b) it is an efficient tool helping practitioners to design water projects optimally; (c) it serves as a guide for policy makers to make appropriate decisions on the subject; (d) it is a robust reference book for researchers, both in universities and in research institutes; and (e) it provides up-to-date information in the field.

Engineers from disciplines such as civil engineering, environmental engineering, geological engineering, agricultural engineering, water resources engineering, natural resources, applied geography, environmental health and sanitation, etc., will find this handbook useful.

Further, courses such as engineering hydrology, groundwater hydrology, rangeland hydrology, arid zone hydrology, surface water hydrology, applied hydrology, general hydrology, water resources engineering, water resources management, water resources development, water resources systems and planning, multipurpose uses of water resources, environmental engineering, flood design, hydrometeorology, evapotranspiration, water quality, etc., can also use this handbook as part of their curriculum.

This set consists of 87 chapters divided into three books, with each book comprising 29 chapters. This handbook consists of three books as follows:

1. Book I: Fundamentals and Applications
2. Book II: Modeling, Climate Change, and Variability
3. Book III: Environmental Hydrology and Water Management

This book focuses mainly on the basic concepts of surface and groundwater hydrology and hydrometeorology, water resources, ecohydrology, and hydroecology in addition to hydrological data processing, flood monitoring, warning, and prediction in urban systems. The second book covers climate and hydrologic changes and estimation, mathematical modeling, risk and uncertainty, spatial and regional analysis, statistical analysis. The third book includes groundwater management, purification, sanitation and quality modeling, surface water management, wastewater and sediment management, water law and water resources management. The chapters in this book can be classified as follows:

- *Dam, reservoir, and hydroelectric*: Long-term generation of scheduling of hydro plants, check dam selection procedures in rainwater harvesting, and stochastic reservoir analysis
- *Ecohydrology*: Ecohydrology for engineering harmony in the changing world, concepts, and plant water use
- *Groundwater hydrology*: Conjunctive use of groundwater and surface water in a semiarid, hard-rock terrain; fundamentals of hydrodynamic modeling in porous media; groundwater exploration: geophysical, remote sensing, and Geographic Information Systems (GIS) techniques; and groundwater hydrology: saturation zone, groundwater–surface water interactions, hydrogeology of hard-rock aquifers, isotope hydrogeology, and karst hydrogeology
- *Hydroecology*: Hydrologic and hydraulic design of green infrastructure, hydrology–ecology interactions, and wetland hydrology
- *Hydrological data*: Data processing in hydrology, optimum hydrometric site selection and quality control, and homogenization of climatological series
- *Hydrometeorology*: Cold region hydrology and evapotranspiration and water consumption
- *Monitoring, warning, and prediction*: Modern flood prediction and warning systems and satellite-based systems for flood monitoring and warning
- *Surface hydrology*: Catchment water yield estimation, hydrograph analysis and baseflow separation, and low flow hydrology
- *Urban systems*: Sustainability in urban water systems and urban hydrology

About 200 authors from various departments and across more than 30 countries worldwide have contributed to this book, which includes authors from the United States comprising about one-third of the total number. The countries that the authors belong to have diverse climate and have encountered issues related to climate change and water deficit. The authors themselves cover a wide age group and are experts in their fields. This book could only be realized due to the participation of universities, institutions, industries, private companies, research centers, governmental commissions, and academies.

I thank several scientists for their encouragement in compiling this book: Prof. Richard McCuen from the University of Maryland, Prof. Majid Hassanizadeh from Utrecht University, Prof. Soroush Sorooshian from the University of California at Irvine, Profs. Jose Salas and Pierre Julien from Colorado State University, Prof. Colin Green from Middlesex University, Prof. Larry W. Mays from Arizona State University, Prof. Reza Khanbilvardi from the City College of New York, Prof. Maciej Zalewski from the University of Łódź, Poland, and Prof. Philip B. Bedient from Rice University.

In addition, Research Professor Emeritus Richard H. French from Las Vegas Desert Research Institute, who has authored the book *Open Channel Hydraulics* (McGraw-Hill, 1985), has encouraged me a lot. I quote his kind words to end this preface:

> My initial reaction to your book is simply WOW!
>
> Your authors are all well known and respected and the list of subjects very comprehensive. It will be a wonderful book. Congratulations on this achievement.

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Editor

Saeid Eslamian is an associate professor of hydrology at Isfahan University of Technology, Iran, where he heads the Hydrology Research Group in the Department of Water Engineering. His research focuses mainly on statistical and environmental hydrology and climate change. In particular, he specializes in modeling and prediction of natural hazards, including floods, droughts, storms, winds, and groundwater drawdowns, as well as pollution in arid and semiarid zones, particularly in urban areas.

Prof. Eslamian received his BS in water engineering from Isfahan University of Technology in 1986. Later, he was offered a scholarship for a master's degree at Tarbiat Modares University, Tehran. He completed his studies in hydrology and water resources in 1989. In 1991, he was awarded a grant for pursuing his PhD in civil engineering at the University of New South Wales, Sydney, Australia. His supervisor was Professor David H. Pilgrim, who encouraged him to conduct research on regional flood frequency analysis using a new region of influence approach. Soon after his graduation in 1995, Eslamian returned to Iran and worked as an assistant professor at Isfahan University of Technology (IUT). In 2001, he was promoted to associate professor.

Eslamian was a visiting professor at Princeton University, Princeton, New Jersey, in 2006 and at the University of ETH Zurich, Switzerland, in 2008. During this period, he developed multivariate L-moments for low flow and soil–moisture interaction.

Eslamian has contributed to more than 300 publications in books, research journals, and technical reports or papers in conferences. He is the founder and chief editor of the *International Journal of Hydrology Science and Technology* and the *Journal of Flood Engineering*. He also serves as an editorial board member and reviewer of about 30 Web of Science (ISI) journals. Recently, he has been appointed as the chief editor for a three-set book series Handbook of Engineering Hydrology by Taylor & Francis Group (CRC Press).

Prof. Eslamian has prepared course material on fluid mechanics, hydraulics, small dams, hydraulic structures, surface runoff hydrology, engineering hydrology, groundwater hydrology, water resource management, water resource planning and economics, meteorology, and climatology at the undergraduate level and material on evapotranspiration and water consumption, open channel hydraulics, water resources engineering, multipurpose operation of water resources, urban hydrology, advanced hydrology, arid zones hydrology, rangeland hydrology, groundwater management, water resources development, and hydrometeorology at the graduate level.

He has presented courses on transportation, Energy and Agriculture Ministry; and different university departments in governmental and private sectors: civil engineering, irrigation engineering, water engineering, soil sciences, natural resources, applied geography, and environmental health and sanitation.

Eslamian has undertaken national and international grants on "Studying the impact of global warming on the Kingdom of Jordan using GIS," "Study of the impact of different risk levels of climate change on Zayandehroud River Basin's climatic variables," "Feasibility of reclaimed water reuse for industrial uses in Isfahan Oil Refining Company," "Microclimate zoning of Isfahan city and investigation of microclimate effect on air temperature, relative humidity and reference crop evapotranspiration," "Feasibility of using constructed wetland for urban wastewater," "Multivariate linear moments for low flow analysis of the rivers in the north-eastern USA," and "Assessment of potential contaminant of landfill on Isfahan water resources." He has received two ASCE and EWRI awards from the United States in 2009 and 2010, respectively, as well as an outstanding researcher award from Iran in 2013.

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Catchment Water Yield

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Jim Griffiths was born in South Wales (United Kingdom) and studied at both undergraduate and postgraduate level in the School of Geography at King's College London. His doctoral research involved spatial modeling of pore-water pressures in shallow translational landslides (in SE England and SE Spain), with respect to climate and land-use change. He spent 5 years as a hydrologist at the Centre for Ecology and Hydrology in Wallingford (formerly the Institute of Hydrology), where his research included development of continuous simulation rainfall–runoff models and investigation of surface water–groundwater interaction in permeable lowland catchments in the United Kingdom. From 2008 to 2011, he worked as senior hydrologist for a UK-based mining consultancy for which he conducted hydrological site investigation work in Sierra Leone, Congo Republic, Burkina Faso, Tanzania, Turkey, and Sweden and contributed to feasibility and prefeasibility level studies for a variety of mine developments in Northern Europe, Central Asia, Africa, South America, and Russia. He is a fellow of the Chartered Institute of Water and Environmental Management (CEng, CEnv, CSci) and a lecturer in environmental sciences at the University of Nottingham Ningbo China.

PREFACE

This chapter describes a number of different approaches for the estimation of catchment yield including water balance, reservoir, and tank models. Emphasis is given to the balance between precipitation and evapotranspiration (ET) by describing the role of different land-use and soil properties in determining the overall water budget. Attention is also paid to the importance of the spatial and temporal scale at which estimates are made and how this might affect their accuracy.

1.1 Introduction

In order to make an assessment of available water resources for a proposed or existing development, one of the first things an engineering hydrologist must do is to estimate the average water yield from surface water catchments. In addition to the estimate of the quantity of available water, the seasonality and interannual variability of catchment yield must be assessed in order to predict the probability of water deficits in drought years and the potential for surplus during wet years. This can be achieved using a range of hydrological models that exhibit varying degrees of complexity. This chapter reviews a number of procedures that can be used to predict catchment water yield, with particular emphasis on consideration of the role of soil and land-use type.

1.2 Definition of the Catchment

The catchment is the principle hydrological unit considered within the field of hydrology and fluvial geomorphology. Catchments can be represented or differentiated by a range of interrelated hydrological parameters including average climate characteristics (precipitation, temperature, and insolation), landform and drainage characteristics (topography, drainage density, channel length, and shape), and soil and land-use characteristics (soil structure and permeability and percentage of canopy cover).

Catchment area is sometimes referred to as drainage area or river-basin area. Catchment yield is the amount of water that will be transported to the catchment outlet from an area of land that lies up-gradient as defined by the surrounding topography. Each catchment is separated from neighboring catchments by a topographically defined drainage divide. Output from smaller catchments will drain into the larger catchments in a hierarchical pattern. A great number of smaller sub-catchments can be defined within any catchment and may be referred to as nested catchments.

In order to do derive catchment water yield, the catchment boundaries, or watershed, should first be identified from topographic maps. Although this can be done manually from contour maps (5–10 m), this is more easily achieved using a digital terrain model (DTM), which can be acquired from photogrammetry, land survey, or remote sensing. Commonly used sources of remotely sensed data include the Shuttle Radar Topography Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Light Detection and Ranging (LiDAR) (see Nikolakopoulos et al. (2006) for a comparison of SRTM and ASTER elevation data and Harris et al. (2012) for description of the use of LiDAR data).

Figure 1.1 illustrates a DTM produced from manually surveyed data points. To achieve greater model accuracy in areas of increased topographic variability, the data are digitized using the triangular irregular network (TIN) method and then are converted into a rectangular grid (5 × 5 m). At this resolution,

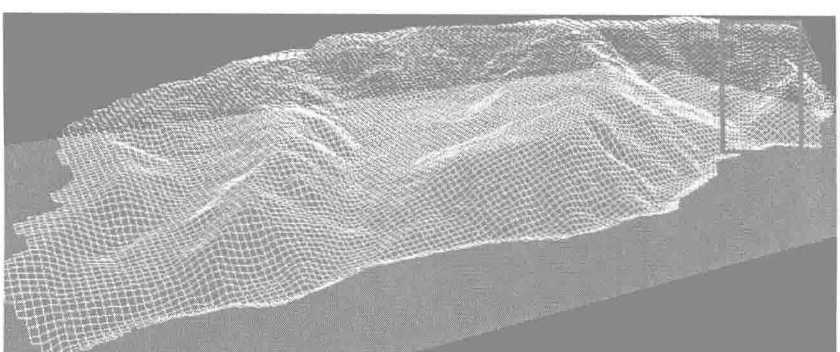

FIGURE 1.1 A 5 × 5 m resolution grid DTM derived from manually surveyed topographic data.

catchments as small as 50 m^2 are identifiable. For larger catchment areas, the use of remotely sensed data and a larger grid resolution may be necessary to reduce computational time. The use of digital topographic data for catchment delineation also allows calculation of fractional areas of different land-cover or soil type if suitable maps are available or if they can be derived from remote sensing imagery data (Rogan and Chen, 2004).

Many water resource models assume surface and groundwater catchment boundaries to be identical. While this is rarely the case (due to soil and geological heterogeneity), it is sometimes a useful assumption to make as it allows hydrological catchment delineation from surface topographic data alone. While both surface and groundwater catchment boundaries associated with a predefined catchment outlet point can be derived manually from paper contour maps or geological maps, this process is more frequently performed using a geographic information system (GIS) or computer-aided design (CAD) software.

1.3 Modeling Catchment Yield

In its most simple form, catchment yield can be defined as the precipitation (P) that leaves the catchment as surface water flow (Q) after Evapotranspiration (ET) losses and losses to the soil or groundwater. If the assumption of a closed groundwater system is made (i.e., there are negligible groundwater losses from or additions to the catchment), catchment yield may be described by a ratio of the difference between mean annual catchment precipitation and ET and catchment outflow (as represented in Equation 1.1):

$$\text{Catchment yield} = \frac{\text{P} - \text{ET}}{\text{Q}} \tag{1.1}$$

Estimation of catchment water yield can be more complex than that expressed in Equation 1.1, especially if a high level of precision and a relatively short time increment is required. Although there are a large range of different models and methods that can be employed by water resource planners and engineers, after definition of the catchment watershed, estimation of catchment water yield can be summarized by four generic steps that should be followed:

- Estimation of catchment inputs
- Estimation of catchment outputs
- Representation of transport processes
- Calculation of catchment yield at the catchment outlet

Assuming there are no upstream inputs, the largest hydrological input into a catchment is precipitation. However, there may be some difficulty in making reliable and representative estimates of catchment precipitation due to both the size of the catchment and the availability of historic data. Firstly, it is more difficult to estimate of precipitation in larger catchments as rainfall is less likely to be homogeneously distributed across the whole catchment or to occur at all locations within the catchment at the same intensity and at the same time. Secondly, the remoteness and extent of human development within a catchment can mean that there is little or no recorded rainfall at any location within the catchment. Both large and remote catchments therefore present a problem that must be solved through the use of the best available data and a number of statistical assumptions about the distribution of precipitation in the area.

It is acknowledged that some catchments will exhibit transboundary groundwater movements, but this is dealt with in more detail elsewhere within this volume (Chapter 22 of *Handbook of Engineering Hydrology: Fundamentals and Applications*). With the assumption of a closed groundwater catchment then, catchment output will consist exclusively of evaporation and transpiration. There are a range of methods to calculate evaporation, the choice of which will depend on available data and the temporal resolution of the required estimate. The maximum rate of water evaporation within a catchment is dependent on water availability. The potential evaporation rate of evaporation is therefore attenuated by