1 Applied Hydrology in the Twenty-First Century

1.1 CONCEPTS AND PURPOSE

The style, contents, and presentation of any subject in a textbook is largely influenced by the philosophy of the author(s) about the subject, developed from experience either in pedagogy or practice and the depth of knowledge gained about the subject. This book is no exception. This chapter presents how the authors view and approach applied hydrology for engineering practice. The concept of a hydrologic system is presented from the view point of thermodynamics, not systems theory. The HEC-HMS software, used throughout the book, is introduced. An abridged account of the history of development of hydrology is presented. This chapter is an orientation of the book.

1.2 HISTORICAL CONTEXT

Hydrology in its broadest definition means science of water. However, today it is used in a much-restricted sense – it is a subject that deals with the amount of water coming to the land surface of the Earth from rainfall, snow, and/or glacial melts and the amount of water available in rivers and streams, lakes, lagoons, wetlands, and groundwater. The development of hydrology began almost concurrently with the flourishment of ancient civilizations in the valleys of the Nile, Tigris-Euphrates, Sindhu (Indus) and Ganga (Ganges), collectively called the Indo-Gangetic Plain, and Huang-Ho (Yellow) rivers. In addition to curiosity-driven developments as a science, hydrology had an early root of development as an engineering discipline because of mankind's invention of irrigation for farming, land development, aqueducts, water supply systems, sanitation systems, and flood control measures from the beginning of human civilizations. Biswas (1970) gave an excellent account of the long history of hydrology tracing back to several millennia. Peters-Lidard (2019) presented a perspective on the development of hydrology during the twentieth century. Giving a historical account of hydrology is not our intention here. However, to put the scope of the present book in the context of development of the subject of hydrology, we follow Ven Te Chow, who described the development of hydrology into several distinct periods starting from the ancient civilization to the time when he wrote the account.

Chow (1964) classified the history of development of hydrology into eight periods with general time divisions as: (i) **period of speculation**, from ancient to 1400; (ii) **period of observation**, from 1400 to 1600; (iii) **period of measurements**, from 1600 to 1700; (iv) **period of experimentation**, from 1700 to 1800; (v) **period of modernization**, from 1800 to 1900; (vi) **period of empiricism**, from 1900 to 1930; (vii) **period of rationalization**, from 1930 to1950; and (viii) **period of theorization**, from 1950 to the time (1964) Chow completed writing the account.

As given above, in the early twentieth century, hydrology was mostly empirical since the physical basis for most quantitative hydrologic determinations was not well known. Rational analysis only started in 1930. LeRoy Kempton Sherman, a civil engineer from Chicago, proposed the unit hydrograph method in 1932 and Robert Elmer Horton, often called the father of American hydrology, propounded the infiltration theory in 1933. French hydraulic engineer Henry Darcy developed the most fundamental law of groundwater flow in 1856. Charles Vernon Theis from the United States Geological Survey (USGS), combined the Darcy law with the continuity equation, which led to a diffusion type equation. By solving this equation, in 1935 Theis derived a relation between the rate of drawdown and the rate and duration of pumping. This revolutionary work laid the foundation of quantitative groundwater hydrology. C. E. Jacob (1943, 1944) correlated infiltration and groundwater which led to the development of techniques for baseflow separation (Barnes, 1940). L. G. Puls (1928) and G. T. McCarthy (1938), both from the United States Army Corps of Engineers (USACE), developed the method of hydrograph routing. The works of Charles Warren Thornthwaite (1948), an American geographer and climatologist and Howard Latimer Penman (1948), an English physicist, paved the path for the quantification of evaporation and evapotranspiration. Emil Julius Gumbel, a German mathematician, introduced the extreme value distribution for frequency analysis of hydrologic data in 1941 and Chow formulated the frequency factor for hydrologic statistics in 1951. These monumental contributions laid the foundation of modern hydrology. Theoretical approaches began about 1950, most notably with the mathematical representation of hydrologic systems as linear and time-invariant systems by stalwarts of hydrology such as James Clement Dooge, James Eamon Nash, both from Ireland, and Chow, who carried out his work at the University of Illinois. An empirical unit hydrograph method developed by Franklin F. Snyder (1938), from the USGS and another unit hydrograph method proposed by

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C. O. Clark (1943), from the United States Engineering Office in Virginia, with a theoretical basis, changed the way hydrologic design calculations were made. Stupendous progress has been made since then in theoretical developments with the application of advanced mathematics.

One name that has not been mentioned very often by those who have narrated the history of hydrology in various writings, as a contributor of certain milestone concepts of applied hydrology, is Victor Mockus. This unintentional absence of his recognition is due to the fact that Mockus was an employee of the Soil Conservation Service (SCS) of the United States Department of Agriculture, and his contributions were published in SCS reports in the 1950s and the 1960s, and credits are given to those reports. But the fact is that Mockus was the originator of the curve number method used for the calculation of runoff volumes that contribute to streamflow, the lag method for computation of watershed time of concentration, and the dimensionless unit hydrograph method, all of which are roped together today as the NRCS method. It is not an exaggeration to say that this is the most popular and widely accepted method worldwide; in spite of the fact that it was developed for the watersheds of the United States, it has an inherent simplicity enabling its adaptability to other parts of the world. A noteworthy point about the dimensionless unit hydrograph that was developed by Mockus, essentially from empirical synthesis of rainfall–runoff records from a large number of watersheds, is that its shape mimics the shape of a unit hydrograph derived from a theoretical gamma distribution, which was proposed by theoreticians such as Nash and Dooge.

Following Robert Horton, Luna Leopold, Walter Langbein, Gordon Wolman, and Thomas Maddock, four remarkable theoreticians, armed with meticulously collected large sets of observational data and all from the USGS, formulated certain laws of geomorphology in the 1950s, such as the discovery of hydraulic geometry relationships and the introduction of the concept of entropy in geomorphology, which have had a lasting impact on applied hydrology.

In the mid-1940s, the Federal Government of the United States initiated a major research program as a cooperative effort between the USACE and US Weather Bureau, with the major impetus being to develop procedures to derive spillway design floods for major dams that were being planned for western river basins subject to snowmelt runoff. The Cooperative Snow Investigation Program established three snow laboratories, which were operated until the mid-1950s. Results of the laboratory experiments and other scientific research of the program were documented in numerous technical reports, research notes, and technical bulletins. These were in turn compiled into a summary report, named *Snow Hydrology*, by USACE in 1956. This document was a landmark contribution in the field of hydrology of snowmelt and still remains a valuable resource for hydrologists and engineers working with applications of snow hydrology.

The last but not the least significant theoretical development, which started in the 1950s and shaped the subsequent mathematical modeling of watershed hydrology, was the development of kinematic and diffusion wave theories. Even though shallow water equations were developed by French mathematician Adhémar Jean Claude Barré de Saint-Venant in 1843, their simplified forms were the basis of physically based hydraulic and hydrologic modeling. Iwagaki (1955) from Japan conceived the kinematic wave concept to develop the method of kinematic wave routing for channel flows and also applied diffusion wave approximation to flow routing in streams and canals. Although this approximation has been applied to rainfall–runoff modeling, a further simplification of the Saint Venant equations has been more popular. This was due to a seminal contribution in 1955 by Lighthill and Whitham from the United Kingdom, who developed the kinematic wave theory for describing flood movement in long rivers. The real impetus to the application of kinematic wave theory was due to the development of the kinematic wave number proposed by Woolhiser and Liggett in 1967. A full account of these theories is given by Singh (1995). Diffusion wave approximation to channel flow routing became popular since, in1969, Jean A. Cunge, a Polish–French engineer, improved the Muskingum method developed by McCarthy and others that is now known as the Muskingum–Cunge method.

With the advent of analog and digital computers, a **period of simulation** started in the 1960s. However, computer technology took a quantum jump in the 1980s when microcomputers were commercialized, analog computers became obsolete, and software engineering started to evolve by leaps and bounds, particularly with the invention of object-oriented programming languages and the graphical user interface (GUI). Various software with widespread circulation and application came into existence. Nonetheless, the revolutionary period of hydrologic modeling began in the 1990s with the arrival of internet technology and the adoption of geographic information system (GIS) technology, which started in the 1980s. Thus, the newest period in the development of hydrology, the **period of modeling with information technology**, had begun. Applied or engineering hydrology at the current stage of the twenty-first century constitutes mostly hydrologic computations through modeling, using digital data and advanced software coupled with GIS software, together with mathematical methods that have reached maturity for their robustness and reproducibility to represent the physical principles of rainfall–runoff processes.

1.3 HYDROLOGIC SCIENCE AND HYDROLOGIC ENGINEERING

Hydrology is legitimately regarded as a geophysical science. Dooge strongly advocated the inclusion of hydrology as a distinct branch of geophysical sciences. However, its origin in civil or water resources engineering cannot be overlooked. Indeed, hydrology originated from the need for designing civil infrastructure facilities, such as water supply systems, urban and rural drainage, flood control works, water impoundments, arterial airfields, land reclamation, river training works, and agricultural irrigation. The need for the appropriate design of such facilities, in turn, gave birth to the development of measurement techniques and tools. Nevertheless, hydrologic science and hydrologic engineering are inseparable and have developed in a complementary fashion, with an understanding of the basic scientific principles and appreciation of the practical applications to further basic research. Hydrology can be viewed both as a geophysical science and an engineering discipline, and one can also justifiably consider hydrology as an environmental science as well as a branch of environmental engineering. It is not important what hydrology is called or where it is placed. What is important at the current time is that hydrology is advanced in all aspects, and water-related questions impacting mankind are answered with a scientific basis due to the advancements made in this subject over the past several centuries. The software and information technology available now has enabled scientists and engineers to obtain and process vast amounts of data of hydrologic importance and perform advanced computations with lightning speed and desired accuracy by bridging the theoretical concepts and applied aspects of hydrology. Even though we have treated the subject matter in light of the advancements of the twenty-first century, our presentation of the subject matter is along the direction in which civil engineers, irrigation and agricultural engineers, and applied earth scientists approach hydrology. For this reason, instead of diving deep into the fundamental science that underlies the principles and practice of hydrology in engineering applications, our emphasis in this book is on the purity of the practice, keeping the rigor of the principles but without delving too much into the scientific description.

1.4 HYDROLOGIC SYSTEMS

A **system** is that part of the universe that is set aside for current consideration and the **surroundings** are the rest of the universe. A system has a set of connected parts called components that form the whole. The system approach in hydrology was perhaps first extensively discussed by Dooge, from the Department of Civil Engineering, University College, Dublin, Ireland, in a 1973 publication resulting from lectures given by him in August 1967 at the University of Maryland in the United States, under the sponsorship of the Agricultural Research Service of the US Department of Agriculture. Dooge (1973) approached hydrologic system essentially from an angle of systems theory of operations research. We will introduce this concept in Chapter 2. Here we introduce a hydrologic system, as it is commonly used in the field of thermodynamics, that deals with energy and mass transfer in various kinds of processes, which can be physical, mechanical, chemical, or biological.

Applied hydrology is all about a system that encompasses a component, which is a piece of land surface, subjected to input that is either rainfall or snow and ice melt, or both, producing output that results in water flowing down the streams present on the land surface. The system has sources and sinks. The water that infiltrates into the surface of the land, percolating down to recharge groundwater, and water that returns to the atmosphere above the land surface are examples of sinks. Other examples of sources of water entering the system are water supplied by a pipe or diversion.

The land surface component of the system is called a **drainage basin**, which assumes names like catchment, watershed, and basin but all have the common characteristics of having a single point called an outlet from which all water from within the unit exits the system. The boundary of this land surface is called the drainage divide. The definitions of the synonymous terms given to a **drainage unit** are discussed in Chapter 6. Treating a drainage unit as a *system* with various interconnected parts or components and atmosphere as its *surrounding* is a fundamental concept that has also been called the **watershed concept**.

A pictorial representation of a hydrologic system is given in Figure 1.1. It has a set of connected parts or components, such as the land surface, streams, the overlying atmosphere, and the underlying subsurface, that form a whole. In thermodynamics, three kinds of system are defined. These are the following: (1) An **isolated system** is one that cannot exchange either mass or

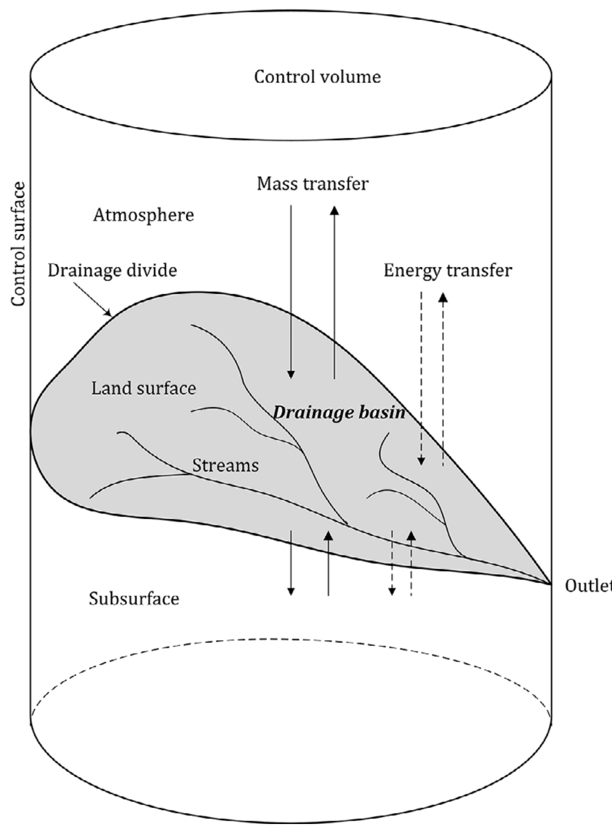

Figure 1.1 Physical representation of a hydrologic system consisting of a land surface component called a drainage basin or drainage unit, the atmosphere over it, and the subsurface. Energy and mass transfer occur in both directions as shown by lines with arrow heads; the dashed lines indicate a process that cannot be "seen."

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energy with its surroundings. A perfect isolated system is hard to come by, but an insulated drink cooler with a lid is conceptually similar to a true isolated system. The items inside can exchange energy with each other, which is why the drinks get cold and the ice melts a little, but they exchange very little energy (heat) with the outside environment or its surrounding. (2) A **closed system** can exchange only energy with its surroundings, not mass. (3) An **open system** can exchange both energy and mass with its surroundings. A system of drainage basin is an open system as shown in Figure 1.1. In continuum mechanics, fluid mechanics, as well as in thermodynamics, a **control volume** or **control space** is a mathematical abstraction employed in the representation of mathematical models of the **physical processes** within a system. The closed surface enclosing the region is referred to as the **control surface**. The connected parts are operated by the hydrologic processes driven by heat engines, and the system is a drainage unit or control space in four dimensions (space and time).

1.5 HYDROLOGIC PROCESSES

Within the control volume of a hydrologic system distinct types of physical and biological processes take place by the work done by the force of gravity and the transfer of energy in the form of heat. We state this as the first law of thermodynamics in Chapter 15. The hydrologic processes are overly complex and hardly fully understood even the present day. Nevertheless, this has not deterred scientists and engineers from developing mathematical representations of the processes by sets of equations that have been working quite well for building engineered systems to manage and utilize water resources successfully.

The hydrologic processes that are of immediate concern for hydrologic engineering depends on the purpose of the engineering project where this engineering has a role. If a water resources project is designed and built to manage water from rainfall–runoff events of a certain magnitude and fixed duration, all of the major hydrologic processes need not be considered. On the other hand, if the project entails a fuller understanding of the hydrology of a drainage basin for the long term, then considerations must be given to a broader set of hydrologic processes. This is illustrated in Figure 1.2 in which the principal hydrologic processes that are typically considered for two distinct types of simulations are shown.

As stated above, for the purpose of engineering, the hydrologic processes are described by sets of equations. These equations contain a set of **variables** and a set of **parameters**. For this reason, engineering hydrology can be called **parametric hydrology**, a term coined by Dooge (1973). Modern parametric hydrology is essentially a simulation of hydrologic processes to attempt an accurate

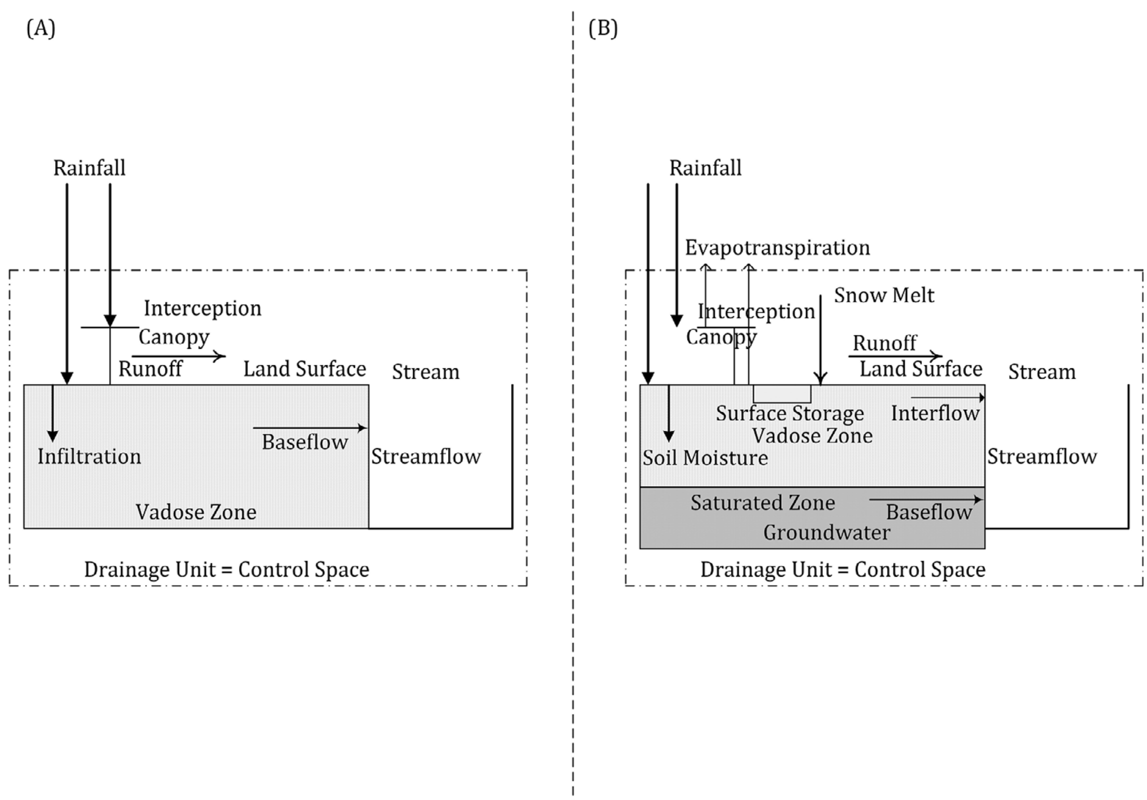

Figure 1.2 Hydrologic processes usually considered in modeling two types of simulations. (A) Processes considered for simulation of rainfall events of finite duration. (B) Processes considered for long-term simulation, also called continuous simulation of rainy and dry periods spanning several months, years, or decades.

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representation of the real-world hydrologic phenomena. This is the field of hydrologic modeling.

1.6 HYDROLOGIC MODELS

The development of hydrologic modeling also has a long history that will not be described here. Singh and Woolhiser (2002) and Singh (2018) provided a perspective account of the development of such models. Many hydrologic models have been developed in the world and most of these are described by Singh (1995) and Singh and Frevert (2002a, b, 2006). The current hardware and software technologies have provided the prowess to model hydrologic processes at varied spatial and temporal scales. Several models have been developed by various governmental and commercial organizations as well as researchers from academia. However, a selected number of those models are currently in widespread use and have become industry standards, particularly for hydrologic engineering practice. There are several reasons behind their widespread adoption world over. First, the models that are in the public domain and can be easily downloaded have a natural appeal to their intended users. In choosing those models, the second consideration is given to the model originators. If a model is developed by a reliable and well-respected organization, particularly if the model is approved by governmental and regulatory agencies, its acceptability is backed by engineering communities involved in developing models for real-world problems and, in particular, projects that entail design for the construction of hydraulic structures. The third consideration given in the adoption of a model is to the methods and concepts that are imbedded in the models. If a model implements well-established methods and principles that have reached their full maturity and are recognized as a standard practice, the model is also considered a standard model. Sometimes consideration is also given to choosing a hydrologic model for its capability to be integrated with GIS software. After all, watershed hydrology is a spatial science and GIS technology offers a tremendous power of combining analytical or computational components of modelling with the spatially distributed nature of the science, which is at the very heart of hydrology of large areas. In addition to these primary considerations, other factors that also come into play for the selection and acceptance of a hydrologic model are the level of training required to learn how to use the model, the continuity of its development, and maintenance or upgrades by the developers, together with the availability of technical support.

1.7 AN INDUSTRY-STANDARD HYDROLOGIC SIMULATION MODEL

1.7.1 Hydrologic Simulation

Applied hydrology revolves around the calculations of volumetric flow rates of water, which result from complex interactions of various hydrologic processes in a matrix of human-made and natural settings. In the modern era of highly advanced software and hardware engineering, virtually all hydrologic calculations are routinely carried out by using a simulation model. Many hydrologic simulation models, either proprietary or in the public domain, are now available. A discussion covering aspects of all of the commonly known hydrologic simulation models is not within the scope of this chapter. Here we only introduce the model that is used in this book, the industry-standard hydrologic simulation model.

1.7.2 Introduction to the HEC-HMS Software

1.7.2.1 Highlights of HEC-HMS

The USACE has led the developments of many methods of applied hydrology for over a century. The Hydrologic Engineering Center (HEC) of USACE developed the numerical model (computer program) HEC-1 in the later part of twentieth century as the age of digital computers emerged. It was a first-generation hydrologic simulation model. With the invention of GUI, HEC-1 transitioned from a computer program to the HEC-HMS software at the advent of twenty-first century. HEC-HMS, which stands for Hydrologic Engineering Center – Hydrologic Modeling System, includes a large set of methods to simulate drainage basin, channel, and water-control structure behavior, thus predicting flow, stage, and timing. HEC-HMS is used throughout all chapters of this book for the following reasons.

1. In the United States as well as in many other countries, HEC-HMS is the current industry standard for simulation and calculations pertinent to hydrologic engineering practice.
2. In the United States it has been used in many studies for achieving goals of flood-damage reduction, reservoir and system operation, floodplain regulation, environmental restoration, water-supply planning, among others.
3. In many countries, including the United States, all governmental agencies have officially adopted HEC-HMS as the hydrologic simulation model to use for studies pertinent to both planning and design.
4. HEC-HMS is maintained and continues to be updated or improved by a well-respected and reliable agency of the Federal Government of the United States.
5. The software is very adaptable because it includes a variety of model choices for each segment of the hydrologic cycle.
6. While almost all well-established, traditional, or conventional methods of engineering hydrology have been implemented in HEC-HMS, it also continues to incorporate recent advances in methodologies that rely on other technologies or disciplines such as GIS, advanced meteorological data input and processing, and statistical methods.
7. The HEC-HMS software mostly utilizes simulation components built from conceptual models. These

models typically rely on empirical data to make predictions about water movement. Nevertheless, many of these models contain parameters with a physical basis and may be estimated from measurable properties of the watershed. These models can function very effectively when calibration data are available. In the ungagged case, it is generally accepted that physically based models are a better choice. HEC-HMS includes many physically based simulation components such as Green–Ampt and Smith–Parlange infiltration components, kinematic wave surface runoff components, Priestley–Taylor potential evapotranspiration components, etc.
8. With the very first release, HEC-HMS was in the public domain. So, it is available to anyone, at any corner of the globe, free of charge.
9. The GUI in HEC-HMS is very well designed. It is relatively easy for the first-time student or practitioner to learn how to use it as opposed to many other models that have very steep learning curves due to cumbersome user interfaces.
10. HEC-HMS is an excellent educational tool for any first-time student in the field of hydrologic models.

1.7.2.2 Basic Structure of HEC-HMS

At the very core of any hydrologic modeling lies the concept of a drainage unit, which is the system under consideration. In HEC-HMS this unit is called a **basin**. This is the same concept discussed in Section 1.4. In HEC-HMS, there are seven elements within a basin, the entire system. The foundation of an HEC-HMS model then rests on the concept of spatial connectivity of these elements. One of the seven elements within a basin is the **subbasin**, the first element of the system. Simply put, either a basin or a subbasin is a land surface area defined by a boundary on which a **sink**, possessing the property of being a singular point, to which all surface water from within that boundary flows into. This is same as the outlet shown in Figure 1.1. So, the sink is the second element of the system in HEC-HMS. The surface water is carried by a channel and its tributaries. These are **reaches**, the third element. On the course of a reach there can be one or more open water bodies like lakes, detention ponds, or storage or flood control reservoirs. Any of these make the fourth element called a **reservoir**, of the system. The fifth element of a HEC-HMS model is a **junction**. A junction is a point where water from one or more elements joins to form the flow to the element immediately downstream of the junction. The sixth element of the system represented by a HEC-HMS model is the **source**. It is a virtual point representing a physical entity that contributes water flow to any of the other six elements of the system. The seventh element that can be present within a basin or the system is a **diversion**. This is also a virtual representation of an entity such as a pump station that changes the direction and rate of water flow. At each computational point, all flows contributing from all the upstream elements are joined to form the combined flow that moves to the next downstream element to which it is connected.

A basin can be variously subdivided into multiple subbasins. However, the governing principle here is that the subbasins are spatially connected from higher to successively lower elevations for the surface water to respect gravity as well as to follow the flow patterns of streams that ultimately drain the basin to that singular point called outlet. Figure 1.3 A shows a small drainage basin in Utah, USA. The area is drained by several streams, all of which go to an outlet located on a major stream named Clear Creek. The HEC-HMS basin model of this tributary system is shown in Figure 1.3B.

Once a basin model is created in HEC-HMS, the next step involves selecting the hydrologic processes that must be considered for a specific model. Each of the processes is modeled according to a method. HEC-HMS offers the option to choose from several common methods or models implemented in the program to represent a process. Each of the methods in turn requires one or more variables and parameters. Inputs of rainfall, and in some cases of energy, are provided and the time window for the simulation also needs to be specified.

1.8 HYDROLOGIC DATA SOURCES

As noted above, the current age of information technology has completely changed the way hydrology is practiced today from the way it was practiced 30 years ago. One of the greatest impacts that the internet era has had on hydrologic studies is the availability of hydrologic data in digital formats from numerous sources. We recognize that it is not possible to list or discuss all the sources of hydrologic data that are presently available. Instead, in each chapter, we refer to sources that are reliable, robust, and predictable in relation to the data required for the simulation of the hydrologic processes and methods discussed in that chapter. For example, we use NOAA, FAO, USGS, and GRDC sources for climatic and streamflow data. References to various modern hydrologic databases such as CLIMWAT and ResOpsUS are made in appropriate places. In the same vein, in many parts of the world such data are still not available, either because they do not exist in the very first place or there is no system implemented for the dissemination of information. In addition, there are examples, like in India, where flow data for transboundary rivers are not made available to the public due to restrictions posed by the government. On the other hand, there are many transboundary rivers; the Danube is an example where intergovernmental agreements have made data freely available.

1.9 ABOUT THIS BOOK

1.9.1 Audience

This book has been prepared for three groups of audiences. The first group consists of senior undergraduate and beginning graduate students in civil and environmental

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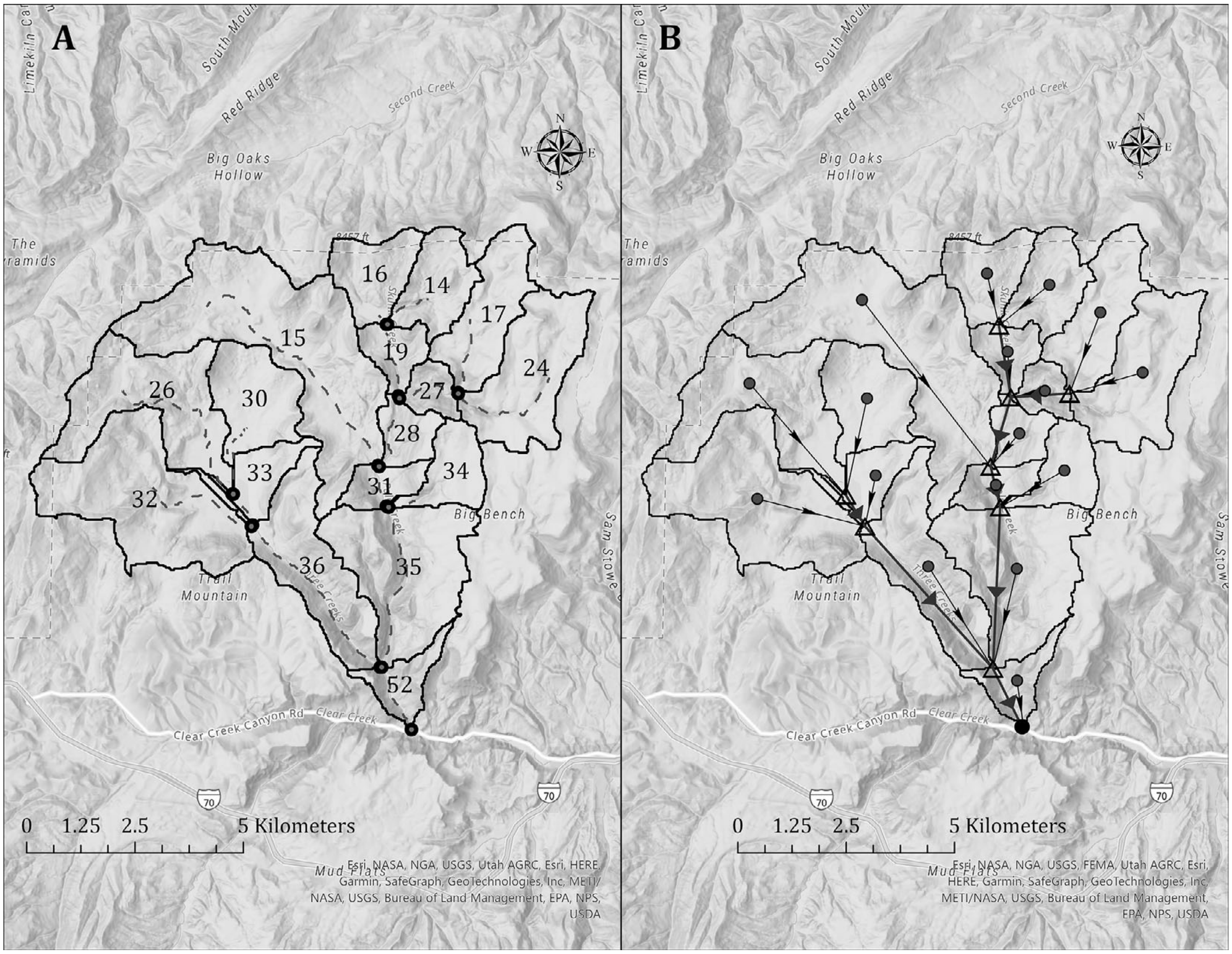

Figure 1.3 (A) A small drainage basin drained by a few tributary channels of Clear Creek in Utah, USA. The drainage basin is subdivided into several subbasins (numbered) and confluences of two streams forming a junction (solid dots). Streams are shown by dashed lines. (B) Abstraction of the physical basin in an HEC-HMS model. Each subbasin is represented by a solid circle. Flow of water from each subbasin to a junction is represented by a thin solid line with a thin arow pointing in the direction of flow. This is overland flow. Each junction is represented by an open triangle. Flow along a reach from one junction to the next junction downstream is represented by a thick solid line with a thick arrow pointing to the direction of flow.

engineering, agricultural engineering, biological or biosystems engineering, natural resources management, and applied earth sciences and their instructors for a serious course in hydrology offered and taken with the intention that the knowledge gained from this course will equip them adequately to enter the profession where they will be practicing hydrologic engineering of the present time. After absorbing the material presented in this book, they should be able to perform their job with confidence and credibility. The second group includes those who are already in the profession of practicing hydrology for engineering applications but, for whatever reason, did not attain the background necessary for the modern standard practice of hydrology. This book can be a companion to them to gain proficiency in the work they do and develop a better understanding and level of confidence in building hydrologic models and perform other calculations, meeting quality requirements that will eventually be used for either design and construction of hydraulic structures or for planning watershed and water resources management. The third group who could also benefit from this book are researchers in hydrology for whom it may be a handy reference, which they can consult either to refresh their knowledge or to see which areas of hydrology are currently important in the practical world.

Each chapter concludes with some worked examples of questions that will help students to test their understanding of the topics covered. Sample exercises are provided as supplementary material and are available at www.cambridge.org/appliedhydrology.

1.9.2 Organization

We have not adopted a traditional approach of writing a book on hydrology, starting with some basics such as the hydrologic cycle, elementary principles of fluid and energy flow;

we assume that those should be common knowledge to those dealing with water science and engineering. We go straight to the point after giving in Chapter 2 an account of the mathematical methods that are necessary to understand various concepts presented in subsequent chapters. A chapter such as this has been conspicuously absent in the currently available textbooks on engineering hydrology. Since most students who need to take an applied hydrology course (with some exceptions), complete college level calculus courses with only an introductory knowledge of differential equations, this chapter will be useful for them as well as to the practitioners who left mathematics classes years ago. An instructor may wish to skip this chapter and ask the students to keep this in mind if they encounter difficulties in following the mathematics in various other chapters.

Then in Chapter 3 we present the principles of probability distribution and certain statistical methods that are also essential to fully comprehend various concepts and methods covered in various chapters. However, the most important contents of this chapter represent hydrologic frequency analysis, which is at the core of hydrologic design, using probabilistic models of rainfall and streamflow.

Throughout the book, we have kept all concepts with a common thread or lineage in one place and have not repeated materials, to aid convenience in learning, consulting, and teaching. For example, in Chapter 3, where we present probability density functions, we only discuss basic types of function, which are referred to in multiple places, but omit those that are specifically used for certain areas, discussing those when we come to the discussions of those areas. For example, we discuss three types of extreme value distributions in Chapter 4 and log Pearson distributions in Chapter 5 in relation to frequency analysis of rainfall and streamflow records, respectively. We have also made a concerted effort to include only those methods and principles that are most often and commonly used in practice. Chapter 3 is another good example of this. There is a multitude of probability distribution functions and, for this reason, most authors tended to list many distributions in a table. We have not attempted to do so since in practice only a few of those are really used and the rest are purely of academic interest, at least for now.

Some topics, which have almost invariably been covered in most existing texts on hydrology, have not been included deliberately in this book, because those subjects are too vast and too important to cover in a single chapter of a textbook primarily focusing on surface water hydrology. It would be an injustice to these very important subjects to include them here. For example, subjects such as groundwater and water quality, in their own right, deserve their own dedicated texts. Fortunately there are some good books that have been written exclusively on subjects like groundwater hydrology and hydraulics and water quality, which are specialized branches of water science and engineering. Anyone interested in any of these subjects should take courses on these subjects that are also routinely offered in most civil engineering and earth sciences programs. In this book, the essential concepts related to groundwater are covered in Chapter 8 in relation to baseflow. After all, groundwater is what makes baseflow.

After presenting methods of measurements and analysis of rainfall and streamflow data in Chapters 4 and 5, respectively, Chapters 6 through 13 cover the topics that are of utmost importance for event-based rainfall–runoff modeling. These models are typically used for hydrologic design or planning purposes.

Chapters 14 and 15 cover evapotranspiration and snowmelt, respectively. Evapotranspiration is especially important for continuous simulation or long-term models. An instructor may choose to cover the evapotranspiration chapter after Chapter 7, dealing with abstraction, since both abstraction and evapotranspiration have the subtraction operation or can be viewed as sinks in accounting of rainfall to runoff.

An important topic that also has been ignored in most texts on hydrology, except for the book by Singh (1992), is erosion and sedimentation. The estimation of erosion potential and sediment yield from a drainage basin has importance in many areas of conservation and resource management. Chapter 16 covers this subject in depth.

Another topic that has also not been discussed in the most well-known texts on hydrology is reservoir operations, which is extremely important for water resources management. This is covered in Chapter 17. The instructors are encouraged to include this topic in their course curriculum to prepare their students for future applications of this knowledge.

Climate change is an extremely important topic of contemporaneous hydrology and is considered in Chapter18. The effects of climate change on rainfall, evapotranspiration, snow covers, and glaciers are discussed in this chapter.

Practicing hydrologists should be cognizant about contemporaneous thoughts and trends in the management of water resources. For example, the Integrated Water Resources Management (IWRM) approach started to emerge during the last couple of decades and is considered by multilateral agencies such as the World Bank and the Asian Development Bank when funding and approving water resources projects in developing and emerging economies. However, the scope of water resources management is not very well established. Davie (2002) delved into this subject, but not in very much depth. We have elaborated on this this topic in Chapter 19, which also covers the water balance of a watershed because of its relevance to the assessment of long-term water availability in these systems.

GIS technology is now fully integrated with modern hydrology. In Chapter 20, we discuss a few specific GIS methods that are commonly used in the development of hydrologic models. This chapter is not a philosophical discussion of GIS technology in hydrology but is written with due recognition that it is not possible to cover all conceivable GIS applications in hydrology in one chapter. Again, this is a topic that merits a book of its own, and indeed some books have already been written on that line. On the other hand, this is a subject that cannot be omitted altogether in a book on applied hydrology prepared in the twenty-first century. So, we have chosen to present certain principles, such as map projection, which are important for an engineer to understand to apply GIS technology in hydrologic studies. We present a few specific applications with hands-on examples to illustrate how GIS software is used to develop and analyze certain data and models for hydrologic modeling. Emphasis has been given to the principles, such as projection systems, geodatabases, processing of vector and raster data etc., so that the concepts are clear to take advantage of the real analytical power of GIS software and not to be viewed simply as a platform to make pretty maps.

Chapter 21 contains the important topic of the optimization of model parameters through the calibration of models. This is a critically important topic for developing reliable models that can be used for the design of hydraulic structures but have been noticeably ignored by most authors of published textbooks on engineering or applied hydrology. Jain and Singh (2019) attempted to give an overview of this topic. HEC-HMS has the capability to use sophisticated optimization techniques for model calibration and these are covered in this chapter. A modern hydrologic design project typically involves the development of hydrologic models of an entire drainage unit and the models integrate some or all of the individual components presented in Chapters 6 through 16 and use GIS software at various stages for varied purposes and by obtaining data from diverse sources. For this reason, we present a holistic discussion of hydrologic modeling as a conclusion to this book. Uncertainty and errors in computations or modeling are also discussed in this chapter.

The organization of the materials discussed above is due to the fact that, for engineering projects where hydrology is involved, only certain processes of the hydrologic cycle are considered at a time, and then only a certain drainage unit of limited spatial extent covering the land surface relative to the land area at the continental scale. Such projects can be major structural flood control engineering measures. Examples include the design of high-volume pump stations on the dry side of levees (in some countries like New Zealand this is called stop banks) and in-line or off-line detention basins with inflow and outflow controls, such as dams, weirs and spillways. Structural flood control measures may also include diversion channels or channel improvements for which event-based hydrologic models of a watershed are necessary. Non-structural measures like flood warning systems require real-time hydrologic simulations. Other examples of projects where hydrologic models are indispensable include urban stormwater management systems involving detention basins and intricate storm drainage networks comprising open and closed conduits; land development projects for the design of new subdivisions or tracts; culverts and bridge crossings along major highways, city arterials, and minor streets; erosion control measures along a reach of a stream; conveyance systems for irrigation and water supply, etc.

1.9.3 Highlights

This book is written within the context of hydrologic modeling with the most up-to-date software packages that are in the public domain but developed by respected and reliable organizations and recognized and adopted by numerous regulatory or governmental agencies worldwide. We have taken advantage, in every aspect of the presentations, of being able to use GIS software. However, fundamentals have not been ignored at any expense. As a matter of fact, the first author finds in his supervisory role in the private sector that one problem being posed by the current era of using sophisticated software as a standard practice is that while the generation of freshly educated engineers entering the field of hydrologic engineering profession gain proficiency in using the software quite quickly they may lack the required depth of knowledge and understanding of the principles. The problem can be attributed to the fact that people can get the results of lengthy calculations without working through the mathematics or calculation steps involved, but by simply entering a set of inputs without realizing that correct inputs in fact do require proper knowledge of the underlying theories or principles of the methods being used. This book is written in order to make a seamless mosaic of the principles and practice of hydrology in engineering applications.

In addition to HEC-HMS, other programs also developed by the HEC are used for specialized applications such as HEC-SSP (Statistical Software Package) for hydrologic frequency analysis, HEC-ResSim (Reservoir Simulation) for reservoir operations, and HEC-MetVue (for visualization and processing of meteorological data). In addition to the hydrologic software developed by the HEC, some other programs or software such as PeakFQ developed by the United States Geologic Survey for flood-frequency analysis are also used in relevant places.

1.9.4 Unit Systems

When an author of a book on the subject of hydrology aimed for engineers and applied scientists is based in the United States and anticipates that practicing engineers in the United States will also use the book, the author faces a dilemma for the choice of the unit system.

The metric system or International System of Units (SI) is the world standard with the exception that in the United States the customary unit is still the so-called English System or foot–pound–second (FPS) system. The availability and accessibility of hydrologic and meteorological data is most ubiquitous in the United States. Those data are also in FPS system, and we use those data extensively throughout the book.

For the reasons given above, we use both the FPS system and SI. We have mostly used FPS system where the original data are obtained in the United States; if the data are obtained in SI from some other sources such as in Canada, UK, Europe, and Australia, we used SI. If we have created any new set of data, then we convert those into SI. For most of the exercises, we used SI. For the same reasons, Chow et al. (1988) and Singh (1992) dexterously used both systems in their examples and exercises.

1.10 EXAMPLES

Example 1.1: Represent the hydrologic cycle in the form of a process flow diagram and discuss how a system of applied hydrology can be considered an open system when the hydrologic cycle at a global scale is a closed system since water circulating within the system always remains within the system.

Solution: There are numerous ways by which the hydrologic cycle in the form of a process flow diagram can be represented. One such diagram, shown in Figure 1.4, is modified from Kulandaiswamy (1964). However, in this diagram the circulation of the runoff from the basin that ultimately flows to the sea from where it returns back into the atmosphere is not shown. In applied hydrology, this process is largely ignored and thereby the system becomes an open system. Thus, at the basin scale, the hydrologic cycle is not a closed system.

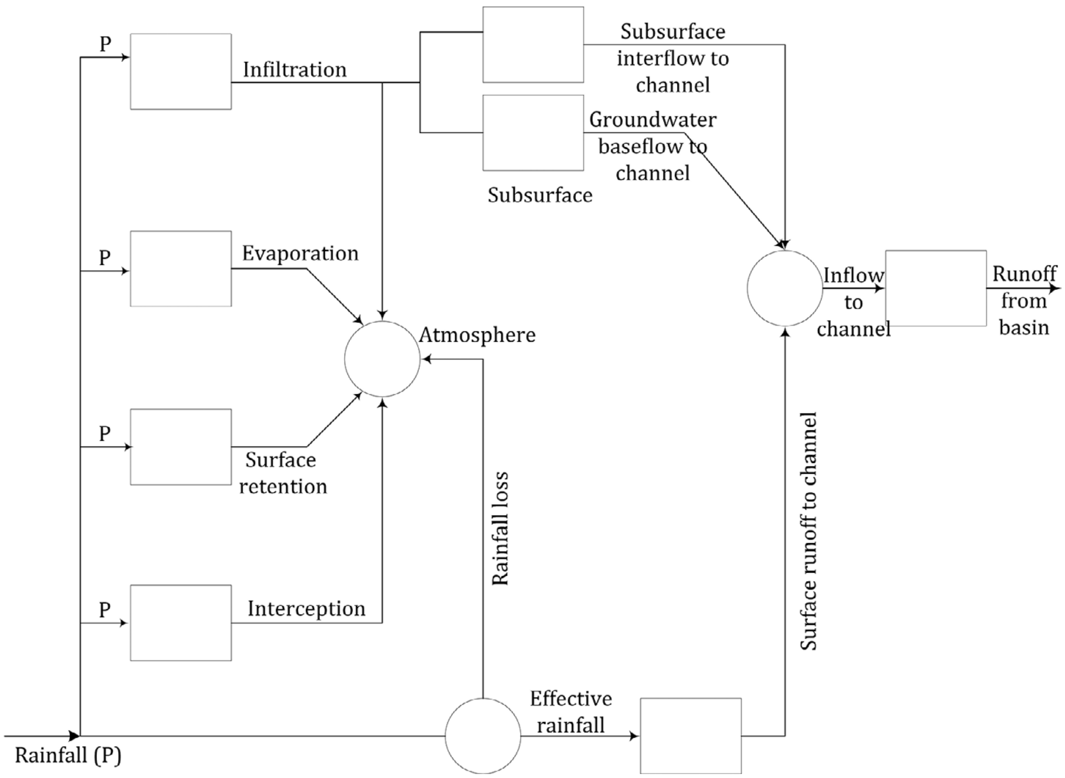

Figure 1.4 A process flow diagram of a partial hydrologic cycle.

Exercises: A selection of exercises on this topic is available at www.cambridge.org/appliedhydrology.

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