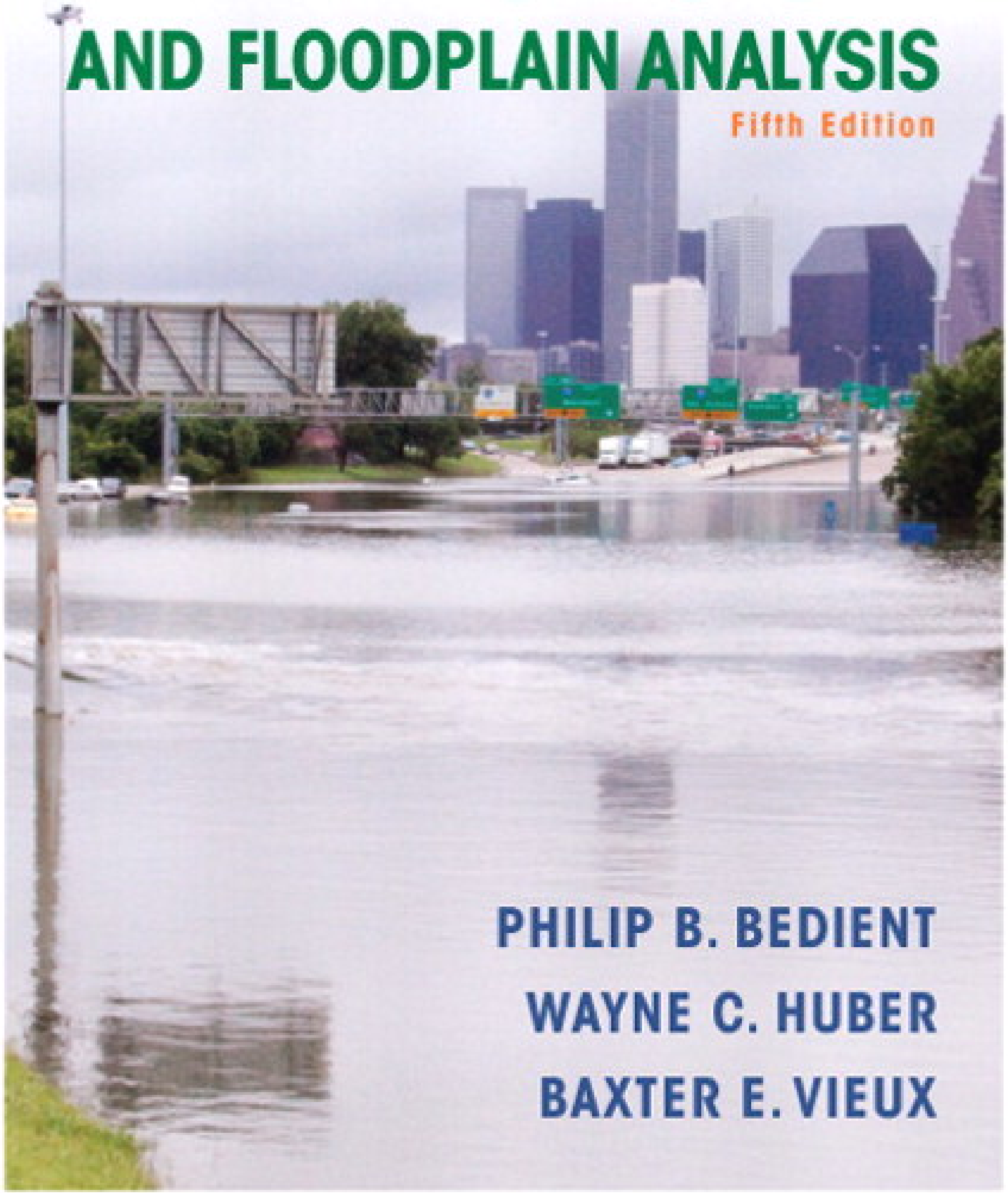
HYDROLOGY

AND FLOODPLAIN ANALYSIS

Fifth Edition



PHILIP B. BEDIENT

WAYNE C. HUBER

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FIFTH EDITION

Hydrology and Floodplain Analysis

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Rice University

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Library of Congress Cataloging-in-Publication Data
Bedient, Philip B.
Hydrology and floodplain analysis / Philip B. Bedient, Wayne C. Huber, Baxter E. Vieux. — 5th ed.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-13-256796-1
ISBN-10: 0-13-256796-2
1. Hydrology. I. Huber, Wayne Charles. II. Vieux, Baxter E. III. Title.
GB661.2.B42 2013
551.48—dc23

2011044526

10 9 8 7 6 5 4 3 2 1

PEARSON

ISBN-13: 978-0-13-256796-1
ISBN-10: 0-13-256796-2

Dedication

To Cindy, Eric, and Courtney,
to my parents for their guidance, and
to my teachers, and to all my students
over the past 35 years.

P.B.B.

To My Family

W.C.H.

To my wife, Jean, and to our children
William, Ellen, Laura, Anne, and Kimberly,
and to my parents

B.E.V.

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PREFACE

The field of hydrology is of fundamental importance to civil and environmental engineers, hydrogeologists, and other earth scientists because of the environmental significance of water supply, major floods and droughts and their management, drainage and urban stormwater issues, floodplain management, and water quality impacts. In recent years, hurricanes and storm surge have caused significant urban disasters, especially along coastal areas where urban development has expanded rapidly. This text was written to address the computational emphasis of modern hydrology at an undergraduate or graduate level, and to provide a balanced approach to important applications in hydrologic engineering and science.

THE EVOLUTION OF HYDROLOGY

Increasing use and sophistication of personal computers has revolutionized the daily practice of hydrology. The Internet has revolutionized the accessibility of hydrologic data and computer models. The impact of transferring online data from governmental and scientific sources to the practicing hydrologist or student has been phenomenal. Hydrologic data, digital terrain models, and mapping software linked with hydrologic modeling have allowed complex problems to be solved. Geographical information systems (GIS) and radar rainfall have greatly improved our ability to predict hydrologic response using distributed information. A number of major improvements have been made to existing hydrologic models, such as HEC and SWMM, and advances in distributed hydrologic modeling such as Vflo. A list of important websites and links currently used routinely in hydrology is contained in Appendix E and can be found at the textbook website: *hydrology.rice.edu*.

NEW TO THIS EDITION

- **Chapter 1:** Extensive updates and changes, and completely rewritten with a more introductory coverage of topics, including simple rainfall runoff and hydrograph analysis with new examples and completely revised homework problems.
- **Chapter 2:** Coverage of the unit hydrograph and includes hydrologic losses such as evaporation and infiltration. New examples have been added on Green and Ampt infiltration, as well as many additional homework problems.
- **Chapter 4:** Expanded coverage and new examples on flood routing. Many of the older numerical schemes have been simplified or removed, and new homework problems have been added to streamline the chapter.
- **Chapter 5:** Presents updated methods for simulating rainfall and runoff, flood hydrograph prediction, and flood control options in a

watershed. New models are highlighted with new examples and a new detailed case study, including flood control alternatives. All new homework problems have been written as well.

- **Chapter 10:** Describes the application of GIS and geospatial information in hydrologic analysis and formulation of hydrologic models. An updated list of available GIS and related software is provided.
- **Chapter 11:** Major advances in detecting accurate and representative rainfall with radar and rain gages are presented. The application of radar rainfall as distributed model input is described. Details on distributed hydrologic modeling are presented for a case study, for which sample datasets are available in Appendix E.
- **Chapter 12:** Reviews the new emerging trends in flood control methods and floodplain management, a vital topic given the recent storm events in the United States, such as Hurricane Irene in the northeast. A detailed discussion of massive hurricane impacts along the Gulf Coast, including Hurricane Katrina and Ike, two of the most damaging hurricanes in history.
- **Chapter 13:** Brand new and includes emphasis on the San Antonio River and Edwards Aquifer System in Central Texas, the Colorado River Basin system, and the Thames River in England. The chapter also briefly highlights international water issues in China and Southeast Asia. The chapter ends with a discussion of the changing global condition and the need for sustainable interaction between human and natural systems.

ORGANIZATION OF THE 5TH EDITION

The 5th edition of the text is divided into three main sections. The first section, consisting of the first four chapters, covers traditional topics in hydrology related to the water balance such as: (1) hydrologic principles, hydrologic cycle, and measurement techniques, (2) hydrologic analysis using hydrographs for rainfall-runoff, (3) statistical and flood frequency analysis, and (4) hydrologic and hydraulic flood routing methods. The second major section, Chapters 5 through 9, is designed to apply hydrologic theory and available hydrologic modeling techniques to several areas of engineering hydrology and design: watershed analysis, floodplain delineation, ground water, and urban stormwater. The latest methods and computer models are emphasized in enough detail for practical use, and updated examples and new case studies are provided.

Chapter 5 on Hydrologic Simulation Models has been completely redone and updated to include the latest model versions as highlighted below in the next section. Chapter 6, Urban Hydrology, presents methods and reviews available computer models for pipe and open channel storm drainage systems. The Storm Water Management Model (SWMM5) is highlighted as the most comprehensive urban runoff model available today. Chapter 7, Floodplain Hydraulics, first reviews concepts from open channel flow and includes uniform flow and critical flow coverage, as required to understand water surface profile computations. The HEC-RAS model is described in detail with a case study demonstrating the power of the model to evaluate natural floodplains. Chapter 8 presents ground water hydrology as a stand-alone chapter, including flow in porous media, aquifer properties, well mechanics, and computer applications. Governing equations of flow are derived and applied to a number of ground water problems, including both steady-state and transient analyses. Chapter 9, written by James Thompson, is a comprehensive chapter on design applications in hydrology. It addresses design rainfall, small watershed design, hydraulic design, detention pond design, detailed culvert design, and floodplain mitigation design issues. It is one of the most comprehensive design chapters ever written and presents both the theory and method behind modern hydrologic and hydraulic design techniques.

In the final section of the 5th edition, three chapters (10, 11, 12) guide the user to the next generation of hydrologic computation, watershed evaluation, and discussion of important severe storm impacts and flood management. No other textbook presents this type of material all in one place. Chapter 13, a new chapter for the 5th edition, presents details of major water resource projects around the world.

Chapter 10 presents the use of geographic information systems (GIS) and digital elevation models (DEMs) as important tools for watershed analysis, hydrologic modeling, and modern floodplain delineation. Many useful hydrologic datasets and software are now widely available in high-resolution digital form on the web (see Appendix E). Chapter 11 depicts some of the latest technology on the use of NEXRAD radar data to estimate rainfall intensities over watershed areas. Radar rainfall has greatly improved our ability to predict rainfall patterns over a watershed and offers real advantages for hydrologic flood alert systems. Distributed hydrologic modeling is introduced that capitalizes on advances in radar rainfall detection.

AUDIENCE AND AVAILABLE RESOURCES

The 5th edition of the text should provide the engineering or science student with all the necessary theory to understand principles of hydrology, hydrologic modeling, floodplain hydraulics and analysis, and water resources in the modern digital world. The student or practicing engineer should find the book a useful reference for hydrologic methods, current models, design examples, and extensively documented case studies. In addition, simple calculations and spreadsheet examples are utilized and highlighted in numerous places in the 5th edition, which contains over 80 worked examples, over 220 homework problems, and 6 major case studies.

The World Wide Web offers many opportunities for access to regional data with minimal cost and effort (see Appendix E), but the U.S. Geological Survey, National Weather Service, National Resources Conservation Service, U.S. Army Corps of Engineers, and other state and local agencies should be emphasized for students as likely sources of regional hydrologic data.

The text includes a Companion website *hydrology.rice.edu* where updates and information can be found regarding the 5th edition. Dr. Bedient maintains the site that contains selected problems, example datasets, simple Excel programs, and dozens of PowerPoint presentations that are available to any instructors and students in the course at no charge. These resources are designed to improve the teaching of a hydrology course at either the undergraduate or graduate level. A detailed solutions manual with updated problems is available for the 5th edition.

ACKNOWLEDGMENTS

The textbook was developed over a period of 25 years, beginning in 1982, from original course notes in a class in Hydrology and Watershed Analysis. During the many years of interaction with colleagues and students, the book evolved into its present form with emphasis on simple examples, clear explanations, and modern computational methods. The 5th edition includes a new Chapter 13 written by Antonia Sebastian and several existing chapters with significant updates such as Chapter 5 (Zheng Fang and George Doubleday) and Chapter 12 (Jude Benavides and Heather Winter).

We are particularly indebted to the following individuals for their careful review of the draft manuscript and for numerous suggestions and comments: Michael Boufadel, Temple University; Stephanie Moret, Louisiana State University; Rao S. Govindaraju, Purdue University; William R. Wise, the University of Florida; and Francisco Olivera, Texas A&M University.

Holly Stark, Executive Editor at Prentice Hall, was instrumental in guiding the significant changes for this 5th edition; the authors thank all the professionals at Prentice Hall for their efforts on our behalf.

A successful textbook always represents a team effort, and the team at Rice University has been excellent in their continuing support and attention to detail. Antonia Sebastian contributed by organizing and writing Chapter 13. Dr. Zheng Fang and George Doubleday contributed to Chapter 5, and Heather Winter added sections and review for Chapter 12. Special thanks are due to students Tatyana Luttenschlager and Roni Deitz at Rice University for their technical skills in reviewing text and figures, and for providing valuable input to examples and homework problems. We would like to thank Erin Baker for helping to organize text, figures, pictures, and permissions for the 5th edition, as well as Mr. Rik Hovinga at Rice University for excellent graphics design, picture selection, and the design of the image that appears on the front cover. We would also like to thank Rice University students Johan Loveless, Alexandra Rasch, and Mike Burcham who assisted greatly in solving examples and developing and checking new homework problems for the 5th edition. Maria Corcuera was also instrumental in helping to organize text and figures for the 5th edition.

Philip B. Bedient, *Rice University*

Wayne C. Huber, *Oregon State University*

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Dr. Bedient has worked on a variety of hydrologic problems, including river basin analyses, major floodplain studies, groundwater contamination models, and hydrologic/GIS models in water resources. He has been actively involved in developing computer systems for flood prediction and warning, and recently directed the development of a real-time flood alert system (FAS2 and FAS3) for the Texas Medical Center (TMC) in Houston. He has built real-time flood alert systems for several communities across Texas. He currently directs the Severe Storm Prediction Education and Evacuation from Disasters (SSPEED) Center at Rice University, an eight-university research organization with private and public entities that predicts and assesses the impacts of severe storms on the Gulf Coast. This center is devoted to developing real-time flood alert and surge alert systems for the coastal areas around Houston such as the Houston Ship Channel, and also evaluates structural and non-structural methods for mitigation of severe storms.

Dr. Bedient has overseen the monitoring, modeling, and remediation at numerous hazardous waste sites, and has extensive experience in contaminant transport at sites impacted with chlorinated solvents and fuels. He has served on two National Academy of Science committees relating to environmental remediation and technology, and has received research funding from NSF, the U.S. EPA, the U.S. Department of Defense, the State of Texas, the U.S. Army Corps of Engineers, the City of Houston, and the Houston Endowment.

Wayne C. Huber is Emeritus of Civil and, Construction, and Environmental Engineering at Oregon State University, Corvallis and Senior Consultant with Geosyntec Consultants, Portland, Oregon. His doctoral work at the Massachusetts Institute of Technology dealt with thermal stratification in reservoirs, for which he received the Lorenz G. Straub Award from the University of Minnesota and the Hilgard Hydraulic Prize from the American Society of Civil Engineers (ASCE). He is a member of several technical societies and has served several administrative functions within the ASCE. He is the author of over 120 reports and technical papers, is a registered professional engineer, and has served as a consultant on numerous studies done by public agencies and private engineering firms.

Beginning at the University of Florida and continuing at Oregon State University, Dr. Huber's research has included studies of urban hydrology, stormwater management, nonpoint source runoff, river basin hydrology, lake eutrophication, rainfall statistics, and hydrologic and water quality modeling. He is one of the original authors of the EPA Storm Water Management Model and helped to maintain and improve the model following its 1971 introduction. Dr. Huber is an internationally recognized authority on runoff quantity and quality processes in urban areas.

Baxter E. Vieux Baxter E. Vieux is a Joseph A. Brandt Professor in the School of Civil Engineering and Environmental Science, University of Oklahoma, Norman. He teaches courses in hydrology, Environmental Modeling, GIS applications, water quality management, and engineering graphics and design. Before joining OU in 1990, he held a professorship at Michigan State University teaching watershed management after earning his PhD there. Prior to his academic career, he spent ten years with the USDA Natural Resources Conservation Service (formerly SCS) serving as Acting State Engineer, and was responsible for statewide engineering design and construction programs in Michigan. He is a registered professional engineer in several states and is co-principal and founder of Vieux & Associates, Inc., an engineering technology company with clients in the US and internationally in radar rainfall, GIS, and hydrology. Dr. Vieux is the innovator and architect of the first commercially available physics-based distributed hydrologic model, Vflo™, which uses real-time radar inputs for hydrologic analysis and prediction. This model is designed for both urban and rural hydrology, and is the subject of a US Patent, 7,136,756 B1, A Method for Determining Runoff. Externally sponsored academic research has been funded by NSF, USGS, NASA, EPA, NWS, NOAA, Army Corps of Engineers, NSF, and state/local agencies. He has authored over 110 publications in hydrology including a recent book in its second edition, Distributed Hydrologic Modeling Using GIS, Kluwer Academic Press, Vol. 48. As a hydrologist, Dr. Vieux has developed radar rainfall monitoring and runoff modeling technology, deployed operational hydrologic forecasting services, and consulted in surface water modeling for a variety of projects and clients in the US. Internationally, he has conducted research and worked on projects dealing with distributed hydrology for a number of agencies.

Chapter 1

Hydrologic Principles

Upper Yosemite Fall, Yosemite National Park. (Photo courtesy National Park Service, U.S. Dept. Interior.)

1.1 INTRODUCTION TO HYDROLOGY

Hydrology is a multidisciplinary subject that deals with the occurrence, circulation, storage, and distribution of surface and ground water on the earth. The domain of hydrology includes the physical, chemical, and biological reactions of water in natural and man-made environments. Because of the complex nature of the hydrologic cycle and its relation to weather inputs and climatic patterns, soil types, topography, geomorphology, and other related factors, the boundary between hydrology and other earth sciences (i.e., meteorology, geology, oceanography, and ecology) is not distinct.

The study of hydrology also includes topics from traditional fluid mechanics, hydrodynamics, and water resources engineering (Maidment, 1993; Mays, 2001). In addition, many modern hydrologic problems include considerations of water quality and contaminant transport. Water quality topics, though important, are not included in this text due to space limitations; they have been covered in a number of modern sources on surface water quality (Huber, 1993; Chapra, 1997; Martin and McCutcheon, 1999) and ground water hydrology and contamination (Bedient et al., 1999; Fetter, 1999; Charbeneau, 2000).

The **hydrologic cycle** is a continuous process in which water is evaporated from water surfaces and the oceans, moves inland as moist air masses, and produces precipitation if the correct vertical lifting conditions exist. The precipitation that falls from clouds onto the land surface of the earth is dispersed to the hydrologic cycle via several pathways (Fig. 1–1). A portion of the **precipitation** P, or rainfall, is retained on the soil near where it falls and returns to the atmosphere via **evaporation** E, the conversion of water to water vapor from a water surface, and **transpiration** T, the loss of water vapor through plant tissue and leaves. The combined loss, called **evapotranspiration** ET, is a maximum value if the water supply in the soil is adequate at all times. These parameters are further discussed in subsequent sections of this chapter and Section 2.6.

Some water enters the soil system as **infiltration** F, which is a function of soil moisture conditions and soil type, and may reenter channels later as interflow or may percolate to recharge the shallow ground water. **Ground water** G flows in porous media in the subsurface in either shallow or deeper aquifer systems that can be pumped for water supply to agricultural and municipal water systems (see Chapter 8).

The remaining portion of precipitation becomes overland flow or **direct runoff** R, which flows generally in a down-gradient direction to accumulate in local streams that then flow to rivers. Hydrologic analysis to determine runoff response from a watershed area is covered in Chapter 2. Evaporation and infiltration are both complex losses from input rainfall and are difficult to measure or compute from theoretical methods, covered in detail in Sections 2.6, 2.7, and 2.8.

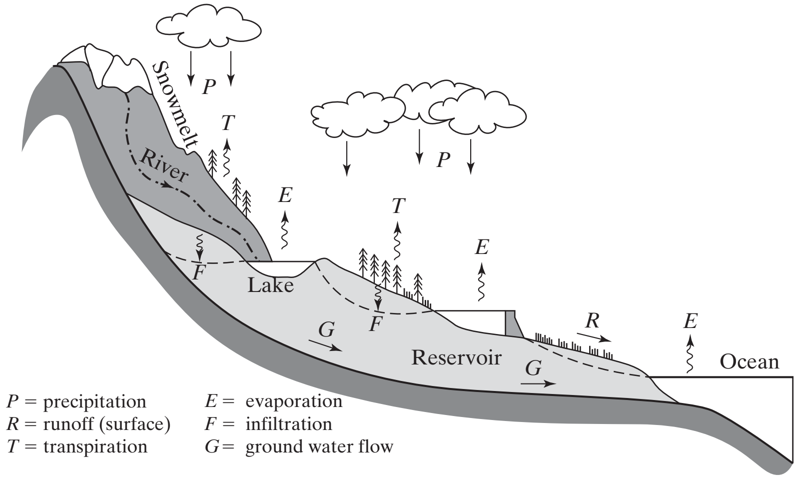

Figure 1–1a
The hydrologic cycle discharges surface water and groundwater from the higher elevation to the lower elevation.

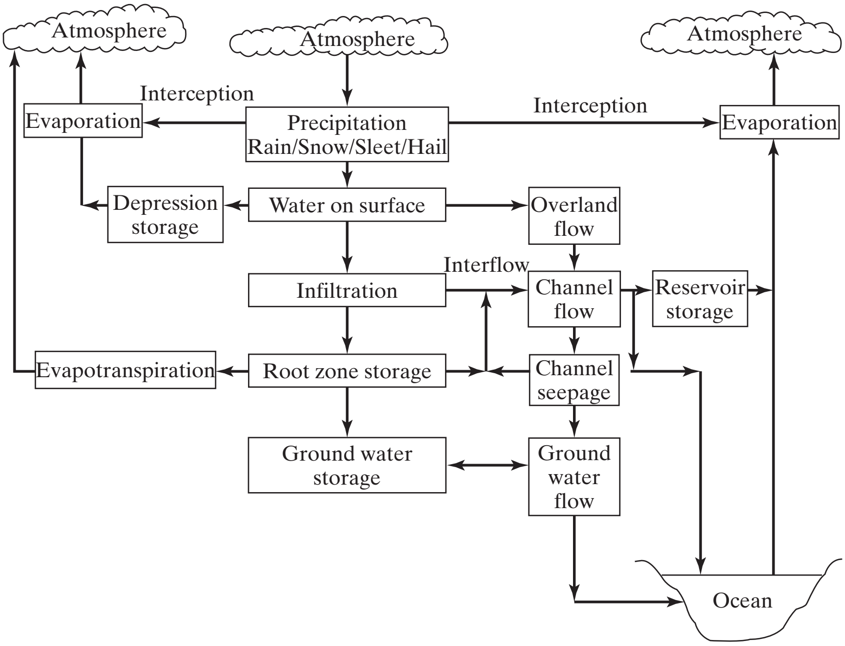

Figure 1–1b
Flow chart of the components of the hydrologic cycle.

Surface and ground waters flow from higher elevations toward lower elevations and may eventually discharge into the ocean, especially after large rainfall events (Fig. 1–1a). However, large quantities of surface water and portions of ground water return to the atmosphere by evaporation or *ET*, thus completing the natural hydrologic cycle (Fig. 1–1b). Precipitation from the atmosphere is a major force that drives the hydrologic cycle, and understanding major weather parameters and systems is important for the prediction of precipitation events (see Section 1.3).

Ancient History

Biswas (1972), in a concise treatment of the history of hydrology, describes the early water management practices of the Sumerians and Egyptians in the Middle East and the Chinese along the banks of the Huang He (Yellow River). Archeological evidence exists for hydraulic structures that were built for irrigation and other water control activities. A dam was built across the Nile about 4000 B.C., and later a canal for fresh water was constructed between Cairo and Suez.

The Greek philosophers were the first serious students of hydrology, with Aristotle proposing the conversion of moist air into water deep inside mountains as the source of springs and streams. Homer suggested the idea

Figure 1–2
Roman aqueducts, known as Pond du Gard located in Southern France, crosses the River Gardon (Gard).

of an underground sea as the source of all surface waters. The Romans constructed numerous aqueducts to serve large cities as well as small towns and industrial sites. The Romans had the largest collection with water being supplied by 11 aqueducts constructed over a period of about 500 years. Figure 1–2 shows one of the famous aqueducts built in France during that early period. They served potable water and supplied the numerous baths and fountains in the city, as well as finally being emptied into the sewers, where the once-used gray water performed their last function in removing wastes. The construction of the Roman aqueducts is considered one of the most important engineering feats in history.

Streamflow measurement techniques were first attempted in the water systems of Rome (A.D. 97) based on the cross-sectional area of flow. It remained for Leonardo da Vinci to discover the proper relationship between area, velocity, and flow rate during the Italian Renaissance. The first recorded measurement of rainfall and surface flow was made in the seventeenth century by Perrault. He compared measured rainfall to the estimated flow of the Seine River to show the two were related. Perrault's findings were published in 1694. Halley, the English astronomer (1656–1742), used a small pan to estimate evaporation from the Mediterranean Sea and concluded that it was enough to account for tributary flows. Mariotte gaged the velocity of flow in the Seine River in Paris. These early beginnings of the science of hydrology provided the foundation for numerous advances in the eighteenth century, including Bernoulli's theorem, the Pitot tube for measuring velocity, and the Chezy (1769) formula, which form the basis for modern hydraulics and fluid measurement.

During the nineteenth century, significant advances in ground water hydrology and hydraulics occurred. Darcy's law for flow in porous media was a major advance, as well as the Dupuit–Thiem well flow formula (Chapter 8). In addition, the Hagen–Poiseuille capillary flow equation was developed to describe flow in small channels. The Darcy-Weisbach equation for pipe flow was also developed during this same period in the 1850s. In surface water hydrology, many flow formulas and measuring instruments were developed that allowed for the beginning of systematic stream gaging. In 1867, discharge measurements were organized on the Rhine River at Basel and quickly expanded throughout Europe.

The U.S. Geological Survey set up the first systematic program of flow measurement in the United States on the Mississippi in 1888. During this same period, the United States founded a number of hydrologic agencies, including the U.S. Army Corps of Engineers (1802), the U.S. Geological Survey (USGS, 1879), the Weather Bureau (1891), and the Mississippi River Commission (1893). The Price current meter was invented in 1885, and Manning's formula was introduced in 1889 (Manning, 1889). The Weather Bureau is now called the National Weather Service (NWS) and is one of six organizations underneath the National Oceanic and Atmospheric Administration (NOAA). NOAA is the agency responsible for weather data collection and severe-storm, river, and hurricane forecasting for the United States, and many of its websites are listed throughout the textbook. The USGS gaging network for rainfall, streamflow, and water quality is one of the most extensive in the world.

Early History (1930s–1950s)

The period from 1930 to 1950, which Chow (1964) called the Period of Rationalization, produced a significant step forward for the field of hydrology, as government agencies began to develop their own programs of hydrologic research. Sherman's unit hydrograph (1932) (see Chapter 2), Horton's infiltration theory (1933), and Theis's nonequilibrium equation (1935) in well hydraulics (Chapter 8) advanced the state of hydrology in very significant ways. Gumbel (1958) proposed the use of extreme-value distributions for frequency analysis of hydrologic data, thus forming the basis for modern statistical hydrology (Chapter 3). In this period, the U.S. Army Corps of Engineers (ACOE), the NWS within NOAA, the U.S. Department of Agriculture (USDA), and the USGS made significant contributions in hydrologic theory and the development of a national network of gages for precipitation, evaporation, and streamflow measurements. The NWS is still largely responsible for rainfall measurements, reporting and forecasting of severe storms, and other related hydrologic investigations.

The U.S. ACOE and the USDA Soil Conservation Service (now called the Natural Resources Conservation Service [NRCS]) made significant contributions to the field of hydrology in relation to flood control, reservoir development, irrigation, and soil conservation during this period. More recently, the USGS has taken significant strides to set up a national network of stream gages and rainfall gages for both quantity and quality data. Their water supply publications and special investigations have done much to advance the field of hydrology by presenting the analysis of complex hydrologic data to develop relationships and explain hydrologic processes. The NWS and USGS both support numerous websites for the dissemination of watershed information and precipitation and streamflow data from thousands of gages around the country. Many of these sites are listed in Appendix E and on the textbook website (http://hydrology.rice.edu/bedient).

The government agencies in the United States have long performed vital research themselves, providing funding for private and university research in the hydrologic area. Many of the water resources studies and large dam, reservoir, and flood control projects in the 1930s and 1940s were a direct result of advances in the fields of fluid mechanics, hydrologic systems, statistical hydrology, evaporation analysis, flood routing, and operations research. Many of the advances from that era continue to this day as the methods to predict runoff, infiltration, and evaporation have not changed much in over 50 years. Major contributions from Horton (1933, 1940, 1941) and from Penman (1948) in understanding hydrologic losses were related to the water and irrigation needs of the agricultural sector in the United States following the devastation of the dust bowl era of the 1930s.

Major water resources projects built during the 1930s were a direct result of major floods on the Mississippi River and the economic depression across the nation. The building of the massive Hoover Dam on the Colorado River for flood and sediment control and water supply in the early 1930s provided employment for over 40,000 and was the largest construction project ever conceived to that point (see Chapters 12 and 13).

Modern History

In the 1950s and 1960s, the tremendous increase of urbanization following World War II in the United States and Europe led to better methods for predicting peak flows from floods, for understanding impacts from urban expansion, and for addressing variations in storage in water supply reservoirs. Major expansion of cities and water systems within the United States during the 1950s led to a need for better understanding of floods and droughts, especially in urban areas. Water resource studies became an everyday occurrence in many rapidly developing areas of the United States, tied to the expansion of population centers in the southern, southwestern, and western states. Hydrologic analyses presented in detail in Chapters 2 through 9 in the text were a major component of many of these studies.

During the 1970s and early 1980s, the evaluation and delineation of floodplain boundaries became a major function of hydrologists, as required by the Federal Emergency Management Agency (FEMA) and local flood control or drainage districts. In order for communities to be eligible for flood insurance administered by FEMA, they are required to delineate floodplain boundaries using hydrologic analysis and models. Floodplain analysis is covered in detail in Chapters 5, 7, 9, and 12. This function has taken on a vital role in many urban areas, as damages from severe floods and hurricanes continue to plague the United States, especially in coastal and low-lying areas. The period from 2004 to 2010 accounted for numerous hurricanes that caused massive damages and deaths in several areas, especially along the coastlines of Texas, Louisiana, Mississippi, Alabama, and Florida. The massive Mississippi flood of 1993 wreaked havoc within the central United States, and was repeated in 2011 with major devastation to states from Illinois south to Louisiana (Chapter 12).

In recent years, the traditional approaches to flood control have been reassessed. A study titled "Higher Ground" from the National Wildlife Federation (1998) found a number of communities with large numbers of repetitive flood losses, such as New Orleans and Houston. Since the great midwestern flood of 1993, there has been a significant shift in national flood policy away from using only structural solutions, such as levee and channel construction. Flood damage from Tropical Storm Allison in Houston in 2001 was a major wake-up call for better protection and warning systems in critical urban areas. The massive devastation from Hurricane Katrina in New Orleans in August 2005 and Hurricane Ike in 2008 in Houston-Galveston will provide long-lasting incentive to improve our ability to warn for and recover from such severe storms. Modern methods for structural flood control, as well as nonstructural approaches, better management of flood-prone areas, and voluntary property buyouts, must be considered in any overall flood management plan (Chapter 12). Chapter 13 explores several major water resources projects across the United States and Asia in terms of engineering significance as well as associated environmental and policy impacts on the nation.

Computer Advances

The introduction of the digital computer into hydrology during the 1960s and 1970s allowed complex water problems to be simulated as complete systems for the first time. Large computer models can now be used to match historical data and help answer difficult hydrologic questions (Singh and Frevert, 2006). The development of these tools over the past few decades has helped direct the collection of the hydrologic data to calibrate, or "match," the models against observation. In the process, the understanding of the hydrologic system has been greatly advanced. Hydrologic computer models developed in the 1970s have been applied to areas previously unstudied or only empirically defined. For example, urban stormwater, floodplain and watershed hydrology, drainage design, reservoir design and operation, flood frequency analysis, and large-river basin management have all benefited from the application of computer models.

Hydrologic simulation models applied to watershed analysis are described in detail in Chapter 5. Single-event models such as HEC-HMS are used to simulate or calculate the resulting storm hydrograph (discharge vs. time) from a well-defined watershed area for a given pattern of rainfall intensity. Continuous models such as the Hydrological Simulation Program—Fortran (HSPF) and the Storm Water Management Model (SWMM) can account for soil moisture storage, evapotranspiration, and antecedent rainfall over long time periods. Statistical models can be used to generate a time series of rainfall or streamflow data, which can then be analyzed with flood frequency methods.

Newer distributed hydrologic models (i.e., VFLO and the MIKE series of models) can handle input, output, and data manipulation at the watershed level (see Chapters 5, 10, 11, and 12). Unquestionably new digital approaches combined with distributed terrain modeling have revolutionized hydrology in recent years, just as the original wave of models did in the decade of the 1970s. Also faster computers and available datasets have been instrumental in advancing the field.

The data revolution in hydrology and geographical information systems (GIS) have made available newer and more accurate datasets on topography, slope, rainfall, soils, land use, and channel characteristics for many areas. Moreover, most hydrological and meteorological data may be retrieved online from agencies such as the USGS and NWS, and various county and municipal sources. These datasets, combined with existing simulation models in hydrology, if applied correctly, provide the most accurate approach to understanding complex water resources systems, and a new era in the science of hydrology has begun this decade. New design and operating policies are being advanced and implemented that could not have been realized or tested before without the aid of sophisticated computer models linked with digital data.

1.2 WEATHER SYSTEMS

The atmosphere is the major hydrologic link between oceans and continents on the planet, facilitating the cycle of water movement on earth. The hydrologic cycle is shaped by the conditions of the atmosphere, with precipitation as the main input to the cycle. Water vapor content is both a major catalyst and a balancing factor of atmospheric processes that create the weather in the lower atmosphere. The following section reviews major elements of atmospheric processes that directly impact the hydrologic cycle. More details on atmospheric processes can be found in modern meteorology and hydrology textbooks (Anthes, 1997; Ahrens, 2000; Dingman, 2002).

Atmospheric Parameters

Pressure is defined as the force per unit area exerted on a surface, and **atmospheric pressure** measures the weight of the air per unit area. Average air pressure at sea level is approximately 1 atmosphere, or 1013 millibars (mb) or 14.7 lb/in.^{2} or 760 mm-Hg or 29.97 in.-Hg. Note that 1 mb $= 10^2$ pascals (Pa), where 1 Pa $= 1$ N/m^2. As elevation increases and the density of air molecules decreases, atmospheric pressure also decreases. The horizontal and vertical pressure variations that occur due to low- and high-pressure systems are responsible for wind, and help drive much of our weather. Absolute temperature (T), pressure (P), and density (ρ) are related through the ideal gas law, $P = \rho RT$, where R is the gas constant for the gas in question (see Eq. 1–1). At constant density, temperature is directly proportional to pressure; thus, with an increase in temperature comes an increase in pressure. Air pressure is proportional to density, so that in the atmosphere a decrease in temperature causes an increase in the density of the air molecules. Cold air masses are generally associated with the higher atmospheric pressure.

Humidity is a measure of the amount of water vapor in the atmosphere and can be expressed in several ways. Specific humidity is the mass of water vapor in a unit mass of moist air. The **relative humidity** is a ratio of the air's actual water vapor content compared to the amount of water vapor at saturation for that temperature. The partial pressure of water vapor is the contribution made by water to the total atmospheric pressure. When a volume reaches its maximum capacity for water vapor, the volume is said to be saturated and can accept no more vapor. This vapor pressure is known as **saturation vapor pressure**. Vapor pressure is dependent on temperature; and as air is lifted and cools, its relative humidity increases until saturation, and then condensation of water vapor to liquid water can occur. The temperature to which a sample of air must be cooled to reach saturation is defined as the **dew point temperature**. These concepts are described in more detail later in this section.

Water vapor has the ability, unique among gases, to change from one state of matter to another (solid, liquid, or gas) at the temperatures and pressures that typically exist on earth. A change in phase (e.g., from liquid to vapor) requires that heat be released or absorbed. The processes of converting solid ice to liquid water, called melting, and water to vapor, called evaporation, both require significant heat exchange. It takes approximately 600 cal to convert 1 g of water to water vapor. When such changes take place, the heat is absorbed and no temperature change takes place. The heat used in this process is latent heat. Condensation is the process in which water vapor changes into a liquid state. For this to occur, energy must be released in an amount equivalent to what was absorbed during evaporation. This latent heat often becomes the source of energy for severe thunderstorms, tornadoes, and hurricanes.

The Atmosphere and Clouds

Atmospheric weather systems are fueled by solar input and characterized by air masses in motion, circulating winds, cloud generation, and changes in temperature and pressure. Lifting mechanisms are required for moist air masses to cool and approach saturation conditions. As a result of the interaction of rising air masses with atmospheric moisture, the presence of small atmospheric nuclei, and droplet growth, precipitation in the form of rain, snow, or hail can result. The exact mechanisms that lead to precipitation are sometimes quite complex and difficult to predict for specific areas. But precipitation remains