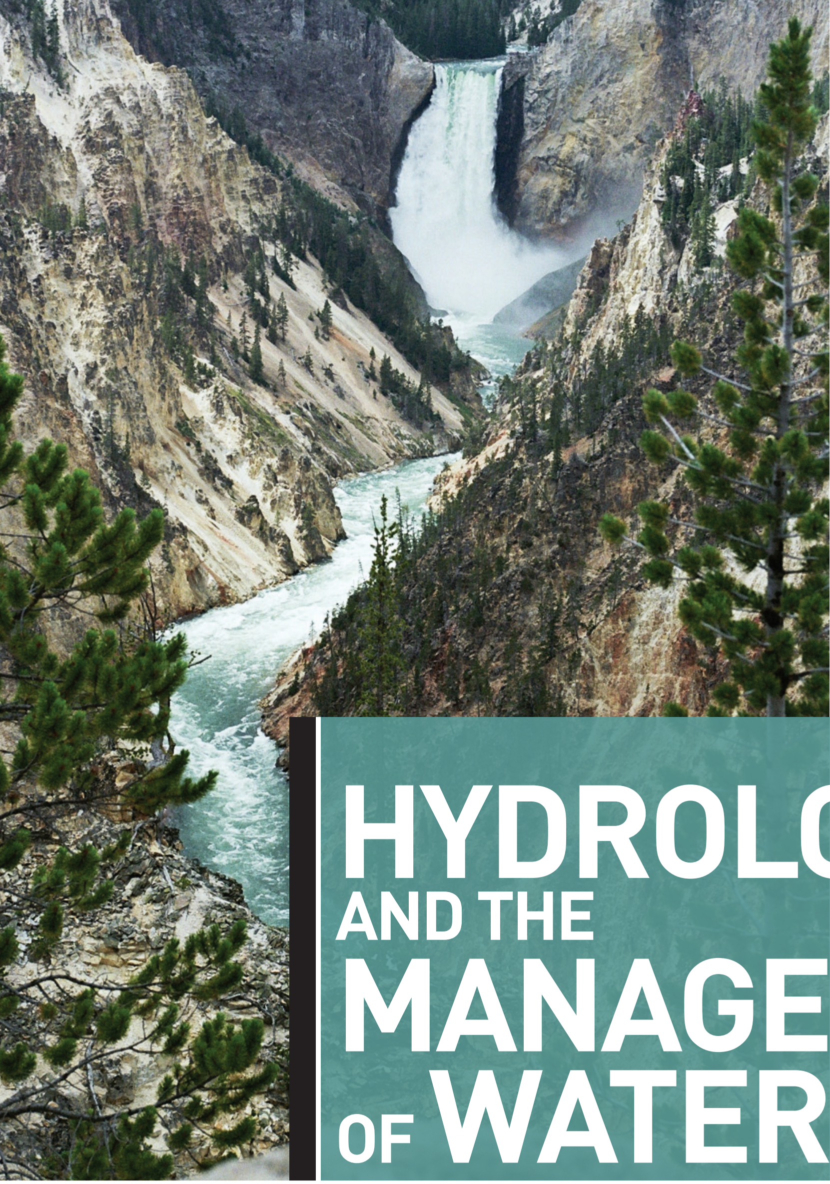

FOURTH EDITION

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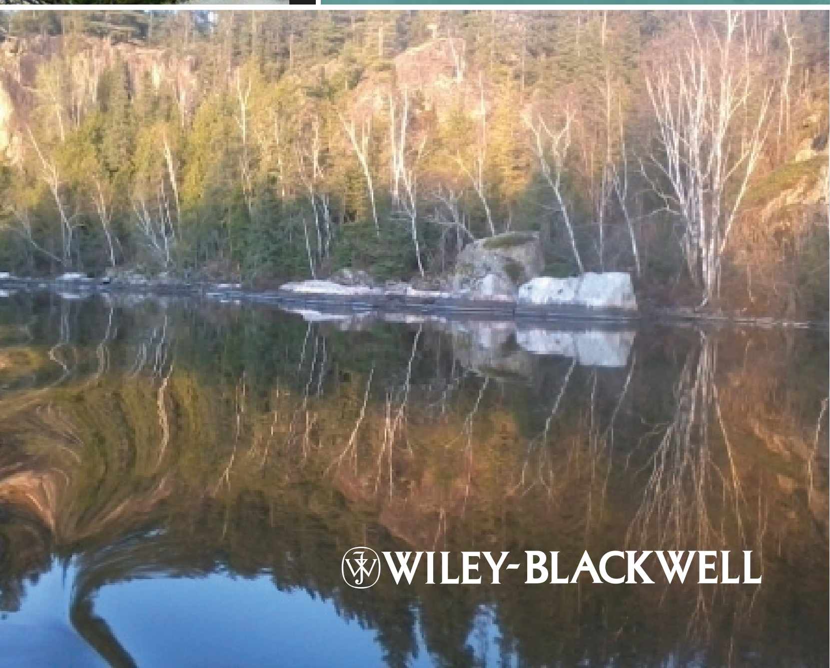

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HYDROLOGY AND THE MANAGEMENT OF WATERSHEDS

A lake scene in northern Minnesota.

Fourth Edition

A waterfall in Guizhou Province, China, illustrates both the beauty and power of flowing water.

Fourth Edition

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Dedicated to

John L. Thames, Hans M. Gregersen, and Leonard F. DeBano

and

Students and the People Who Manage Land and Water for Future Generations

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PREFACE

The fourth edition of this book is a major revision and restructuring of the earlier editions. The basic concepts and fundamental aspects of hydrology and hydrologic processes have been retained with the methods and applications of the science of hydrology in the management of watersheds. We have eliminated the separate chapters on snow hydrology, water resources development and engineering applications, and hydrologic methods contained in the earlier editions. The subject matter in these chapters has not been eliminated in this edition, but rather it has been integrated into chapters that emphasize the hydrologic processes, methods, and applications of integrated watershed management (IWM).

Given the accessibility of information through the Internet and the rapid advancement of technologies, we have referenced URLs throughout the book and presented them in **Webliographies** at the end of the chapters. This approach facilitates the acquisition of current methods, models, baseline data summaries, and applications of technologies for coping with today's challenging issues of changing land and water use and climatic variability.

The chapters in **Part 1 – Watersheds, Hydrologic Processes, and Pathways** – present an updated foundation for the study of hydrology and watershed management. Basic properties and principles of water and energy relationships on earth are presented that provide a basis for understanding the circulation, water form transformations, and flow processes that occur on watersheds. Subsequent chapters build on this basic foundation and concentrate on hydrologic processes and methods of measurement and analysis as presented in the earlier editions. Noted changes include topics of snow measurement and snowmelt processes covered in the chapter on precipitation; hydrologic methods of estimating streamflow characteristics are presented in the chapter on streamflow measurement and analysis; and an expanded chapter on groundwater that examines groundwater–surface water exchanges. The chapters in **Part 2 – Physical, Chemical, and Biological Linkages of Water Flows** – have been structured to reflect the current understandings of soil erosion processes and control of these processes; accumulation and movement of sediment in a stream channel; and the hydrologic linkages to water quality. A new chapter emphasizing geomorphology, valley and channel forming processes, evaluation, and classification is also included in this part of the book. **Part 3 – Integrated Watershed Management** – combines and updates much of the information presented in the third edition of the book into chapters on the management of forests, woodlands, rangeland watersheds for maintaining and where possible enhancing the flows of high-quality water from watersheds. The separate chapters on riparian systems and wetlands found in earlier editions of the book have been combined in a chapter on managing these ecosystems within the context of a watershed landscape. A chapter on the effects of fragmenting wildland watersheds into agricultural and urban areas; implementation of "best management practices"; the importance of regulatory compliance, and coping with climatic variability are contained in this part of the book. Socioeconomic considerations of watershed management are presented in a chapter. A chapter on tools and emerging technologies available to managers for more efficient and responsive watershed management concludes the book.

This fourth edition of the book is intended largely for introductory college courses in hydrology and watershed management. However, the book can also serve as a reference for personnel of governmental and nongovernmental organizations with responsibilities for the management of land, water, and other natural resources on watershed landscapes. The book is also suited for international audiences with examples of watershed processes and the management of land and water extending beyond the US borders. Examples of applications are liberally presented in the text and in boxes throughout the book to help students understand how basic principles and methods can be applied in practice.

Metric (SI) units are used in the book with the exception of where original formulas, figures, tables, and other unit-dependent relationships were developed originally in English (customary) units and where the conversion to metric units is awkward. A table of metric to English units is presented in an appendix to assist the reader in making conversions if desired.

The authors thank Clara M. Schreiber once again for her dedicated work in the preparation of this fourth edition. Clara has also been a partner in all of the earlier editions of the book. The contributions of Hans M. Gregersen, the late John L. Thames, and Leonard F. DeBano – collaborating authors of the earlier editions of this book – have been integral to the evolution of this fourth edition and are greatly appreciated. The contributions of Mark Davidson, Britta Suppes, Linse Lahti, Mary Presnail, Peter Magner, and Dain Brooks in providing new figures and photographs are appreciated. They have improved the visual presentations of the book.

DEFINITION OF TERMS

Hydrology is the science of water concerned with the origin, circulation, distribution, and properties of waters of the earth.

Forest Hydrology/Range Hydrology/Wildland Hydrology refer to branches of hydrology that deal with the effects of vegetation and land management on water quantity and quality, erosion, and sedimentation in the respective settings.

A **watershed or catchment** is a topographically delineated area drained by a stream system; that is, the total land area above some point on a stream or river that drains past that point. A watershed is a hydrologic unit often used as a physical-biological unit and a socioeconomic-political unit for the planning and management of watershed resources.

River basin is similarly defined but is a larger scale. For example, the Mississippi River Basin, the Amazon River Basin, and the Congo River Basin include all lands that drain through those rivers and their tributaries into the ocean.

Integrated watershed management is the process of organizing and guiding land, water, and other natural resource use on a watershed to provide desired goods and services to people without affecting adversely soil and water resources. Embedded in the concept of integrated watershed management is the recognition of the interrelationships among land use, soil, and water, and the linkages between uplands and downstream areas.

Watershed management practices are those changes in vegetative cover, land use, and other nonstructural and structural actions taken on a watershed to achieve watershed management objectives.

HYDROLOGY AND THE MANAGEMENT OF WATERSHEDS


A lake scene in northern Minnesota.

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PART 1

Watersheds, Hydrologic Processes, and Pathways

Photo 1. Measuring groundwater levels in a forested wetland with a pressure transducer in a shallow well (Photograph by Chris Lenhart) (For a color version of this photo, see the color plate section)

Hydrology and the Management of Watersheds, Fourth Edition. Kenneth N. Brooks, Peter F. Ffolliott and Joseph A. Magner.

Knowledge of the inherent characteristics of a watershed and hydrology provides the foundation for understanding the role of *integrated watershed management* (*IWM*) in achieving sustainable development and the use of land and water. An understanding of the hydrologic cycle and energy relationships on earth is fundamental to the study of hydrology and, therefore, necessary for making informed decisions in planning and implementing IWM practices. Embedded in this knowledge is an understanding of the nature of precipitation falling on the watershed; the magnitudes of evaporation, interception, and transpiration losses on a watershed; the infiltration and percolation of precipitation reaching the ground surface; and the pathways of water flow into stream channels and recharging groundwater aquifers. Methods of measuring or estimating streamflow discharges, including peak flows, minimum flows, volumes of flow, and the routing of streamflow from the watershed of origin to downstream points are also basic to understanding hydrology. Concepts of groundwater hydrology and processes of groundwater and surface water exchange are fundamental in understanding surface water–groundwater relationships in watersheds. Part 1 of this book focuses on obtaining this information.

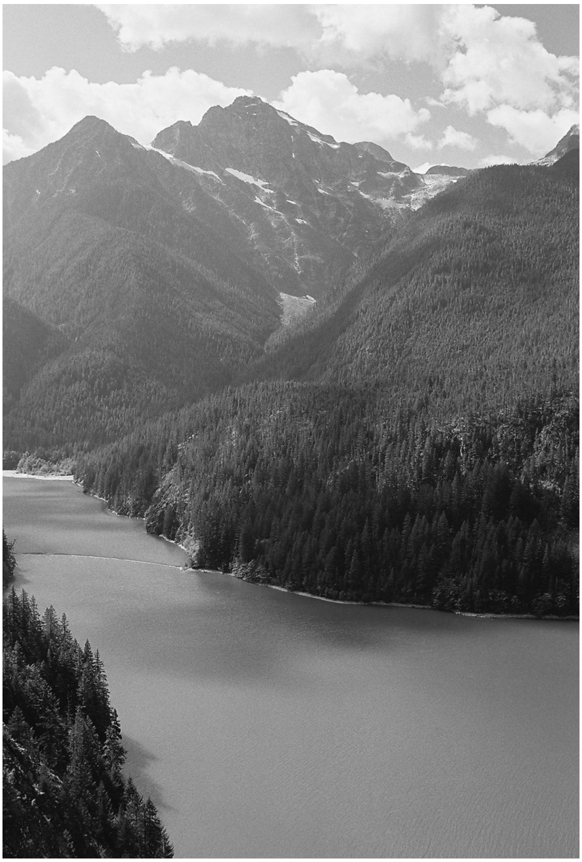

Photo 2. Forested headwater watersheds are the source of most of the streamflow in the United States as depicted in this scene in the Northern Cascades of Washington (Photograph by Mark Davidson) (For a color version of this photo, see the color plate section)

Hydrologic processes are described in detail in Part 1. The topics presented in Chapter 1 of the book include a discussion on the inherent characteristics of a watershed; the importance of IWM; and fostering the sustainable use and development of natural resources while coping with land and water scarcity. Chapter 2 focuses on the hydrologic cycle, the water budget, the energy budget, and the energy processes that drive the hydrologic cycle. Precipitation, including rainfall and snowfall – primary inputs to the water budget, are considered in Chapter 3. The processes of evaporation, interception, and transpiration losses and their importance are discussed in Chapter 4. Infiltration processes and measurement and the pathways of water flow within a watershed system including groundwater recharge are the primary topics of Chapter 5. Methods of measuring and analyzing the streamflow response of watersheds are presented in Chapter 6. Basic concepts of groundwater and groundwater–surface water exchanges are presented in Chapter 7. The collective information in these chapters is basic to hydrology and provides the background necessary for a more comprehensive appreciation of how climatic factors, watershed characteristics, and land-use activities affect the hydrologic responses of watersheds.

PHOTO 3. Students measuring streamflow with a current meter (Photograph by Lucas Bistodeau) (For a color version of this photo, see the color plate section)

CHAPTER 1 *Introduction*

OVERVIEW

Our perspective of watershed management is that water and land resources must be managed in concert with one another. While hydrology and water quality are essential components of watershed management and are the subjects of much of this book, we also recognize the importance of ecosystem functions, land productivity, stream-channel morphology, and the actions of people on the land as integral parts of watershed management. To emphasize this holistic view, the concept of *Integrated Watershed Management* (*IWM*) is embedded in discussions presented in the chapters of this book. IWM deals not only with the protection of water resources but also with the capability and suitability of land and vegetative resources to be managed for the production of goods and services in a sustainable manner. Few watersheds in the world are managed solely for the production of water. Some municipal and power company watersheds that drain into reservoirs are the exception. Since water affects what we do on the landscape, watersheds serve as logical and practical units for analysis, planning, and management of multiple resources and coping with water issues regardless of the management emphasis.

A basic understanding of hydrology is fundamental to the planning and management of natural resources on a watershed for sustainable use. Hydrology enters explicitly and directly into the design of water resource projects including reservoirs, flood control structures, navigation, irrigation, and water quality control. Knowledge of hydrology also helps us in balancing the demands for water supplies, avoiding flood damages, and protecting the quality of streams, lakes, and other water bodies.

One of our concerns and an incentive for writing this book is that hydrology is not always considered in the management of forests, woodlands, rangelands, agricultural

Hydrology and the Management of Watersheds, Fourth Edition. Kenneth N. Brooks, Peter F. Ffolliott and Joseph A. Magner.

croplands, or in the array of human development activities on rural landscapes even though it should be! Ignoring development and land-use effects on soil and water resources is shortsighted and can lead to unwanted effects on a site and in downstream areas. For example, altering forested uplands, riparian communities, and wetland ecosystems can affect the flow and quality of water. Changes in vegetative cover that increase soil erosion can lead to soil instability and long-term losses of plant productivity. The consequences of soil erosion on upland watersheds can alter streamflow quantity and quality downstream. Changes in streamflow and sediment transport can, in turn, alter stream-channel morphology and affect the stability of rivers.

Hydrologic concepts and concerns about land use and water date back to some of the earliest recorded history. The evolution of hydrology from Egyptian texts as early as 2500 BC, to the ancient Indian writings from Vedic times before 1000 BC, to decrees recognizing the interrelationships between water and forests in Europe following the Dark Ages, to contemporary publications into the twenty-first century all illustrate the growing awareness of the importance of hydrology to the management of water and other natural resources. A more detailed timeline of the history of hydrology and watershed management is presented in Box 1.1.

Box 1.1

A Historical Look at Hydrology, Water, Watershed Management, and People

Year	US population[a]	Event	Reference
2125 BC	?	Canals move water from Nile River to supply water for irrigation and human consumption	Baines (2011) (www.bbc.co.uk)
1000 BC	?	An understanding of the hydrologic cycle was indicated in Indian texts from the Vedic times	Chandra (1990)
~900 BC	?	Chinese scholars develop an accurate understanding of the hydrologic cycle	Kittredge (1948)
~360 BC	?	Plato writes about land degradation, flooding, and erosion	Kittredge (1948)
1342	?	The first written record of a “protection forest” being established by a community in Switzerland	Kittredge (1948)

Year	US population[a]	Event	Reference
ca 1670	~110,000 (immigrants)	Perrault accurately quantifies the water balance of the Seine River watershed in France	Kittredge (1948)
1897	72 million	Organic Act . . . authorized the establishment of National Forests on public lands in the west	Glasser (2005)
1903	81 million	Gifford Pinchot publishes *A Primer of Forestry* in which he states "A forest, large or small, may render its service in many ways . . . especially against the dearth of water in streams."	Pinchot (1903)
1909	90 million	Wagon Wheel Gap paired watershed experiment initiated in Colorado	Bates and Henry (1928)
1912	95 million	Raphael Zon publishes *Forests and Water in Light of Scientific Investigation* as an appendix to the Report of the National Waterways Commission	Zon (1927)
1930s	123 million	Coweeta Hydrologic Laboratory founded near Asheville, North Carolina	Ice and Stednick (2004)
1950s and 1960s	151–179 million	Watershed studies established at H.J. Andrews, Oregon; Fool Creek, Colorado; Beaver Creek, Arizona; Fernow, West Virginia; Hubbard Brook, New Hampshire; Marcell, Minnesota; and other "barometer watersheds" on National Forests	Glasser (2005) Ice and Stednick (2004)
2010	308.7 million	US population; more than 1200 locally led watershed management districts, associations, partnerships, councils, and river basin commissions emerged for resolving watershed problems and achieving the goals of IWM	US Census Bureau

Source: US Census Bureau; 2010 population from website: http://2010.census.gov/2010census/data/
[a] Linearly interpolated from decadal census data.

Watersheds

Watersheds are biophysical systems that define the land surface that drains water and water-borne sediments, nutrients, and chemical constituents to a point in a stream channel or a river defined by topographic boundaries. Watersheds are the surface landscape systems that transform precipitation into water flows to streams and rivers, most of which reach the oceans. Watersheds are the systems used to study the hydrologic cycle (see Chapter 2), and they help us understand how human activities influence components of the hydrologic cycle.

Watersheds and Stream Orders

Watersheds and stream channels can be described according to their position in the landscape. It is useful to refer to an established nomenclature of stream orders (Horton, 1945; Strahler, 1964) in discussing watersheds and the water in streams that emanates from them. The commonly used method of stream orders classifies all unbranching stream channels as *first-order streams* (Fig. 1.1). A *second-order stream* is one with two or more first-order stream channels; a *third-order stream* is one with two or more second-order stream channels, and so forth. Any single lower stream juncture above a larger order stream does not change the order of the larger order stream. Thus, a third-order stream that has a juncture with a second-order stream remains a third-order stream below the juncture.

The watershed that feeds the stream system takes on the same order as the stream. That is, the watershed of a second-order stream is a second-order watershed and so on. While there is little evidence that streamflow and watershed characteristics are related to stream order, the use of this terminology helps one place a stream channel or a watershed in the context of the overall drainage network of a river basin. The physical and biological characteristics of watersheds and the climate in which they exist determine the magnitude

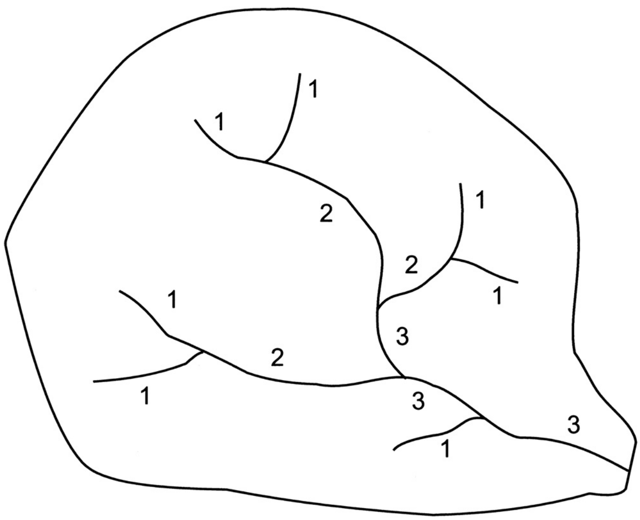

Figure 1.1. Stream order system by Horton (1945) as modified by Strahler (1964)

and pathways of water flow. Furthermore, the hierarchy of watersheds within a river basin generally influences the magnitude of water flow.

A Geomorphologic Perspective

As the upper-most watersheds in a river basin, first-order watersheds, also called *headwater watersheds*, are the most upstream watersheds that transform rainfall and snowmelt runoff into streamflow. Headwater streams comprise 70–80% of total watershed areas (Sidle et al., 2000) and contribute most of the water reaching the downstream areas in river basins (MacDonald and Coe, 2007). Headwater watersheds are often forested or once were prior to the expansion of agriculture, urban areas, and other human development activities. These headwaters are particularly important in water resource management. First-order streams in mountainous regions occur in steep terrain and flow swiftly through V-shaped valleys. High rainfall intensities can erode surface soils and generate large magnitude streamflow events with high velocities that can transport large volumes of sediment downstream. Over geologic time, mountains erode and sediment becomes deposited downstream (Fig. 1.2). As water and sediment from headwater streams merge with higher order streams, sediment is deposited over vast floodplains as rivers reach sea level. A transitional zone

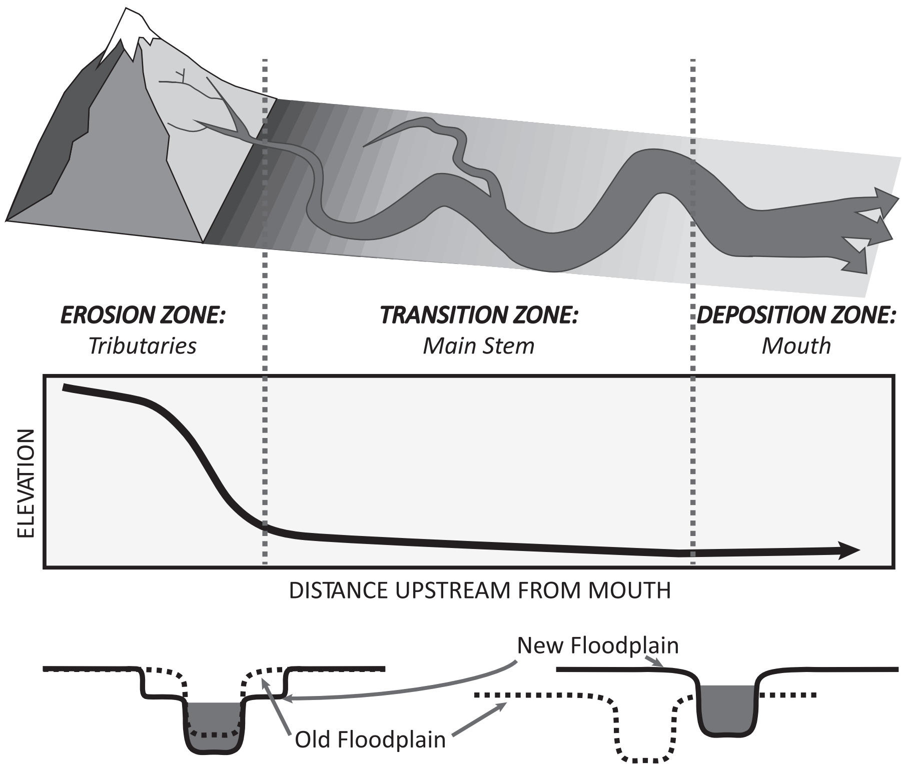

FIGURE 1.2. Rivers generally flow from an upper, high-gradient erosion zone through a transition zone to a low-gradient deposition zone (Schumm, 1977, as modified by Verry, 2007)

exists between the steep headwater steams and the lower zone of deposition at the mouth of major rivers and is typically characterized by broad valleys, gentle slopes, and meandering streams.

The "work" of water on soils, hillslopes, and within rivers forms landscapes with topography and soils that are better suited for some types of land use than others. Agricultural centers have developed in the transitional and depositional areas of a river basin while the steeper uplands are likely to prohibit intensive agricultural cultivation, resulting in landscapes with forests, woodlands, and rangelands suitable for forestry and livestock-grazing enterprises.

Watershed Assessments

The hydrologic response of watersheds to climatic variability and land-use changes will be discussed in this book requiring that methods of delineating watershed boundaries, determining watershed areas, and assessing a myriad of watershed metrics be understood. *Geographic Information Systems* (*GIS*), maps, and other tools, such as *Google Earth*, provide the means to quantify and describe watersheds, their vegetative cover, geology, and soils, and help delineate people's activities occurring across the landscape. Physical descriptions, such as watershed area, slope, stream-channel lengths, and *drainage density* (the sum of all channel lengths in a watershed divided by the watershed area), are important descriptors of watersheds.

Considerable information is available for assessing watersheds in the United States. *Hydrologic Unit Codes* (*HUCs*) are used by the U.S. Geological Survey to classify four levels of hydrologic units beginning with 21 major geographic regions that contain either major river basins or a series of river basins in a particular region. The major regions are subdivided into 221 subregions with 378 accounting units and ending with 2264 watershed units (Seaber et al., 1987). HUCs are used for mapping and describing areas on the landscape and in some cases coincide broadly with ecoregions (Omernik, 2003). HUCs can be watersheds or other land units that have similar characteristics of climate, vegetation, geology, soils, land use, and topography. As such, HUCs would be expected to have common hydrologic properties that differ from those HUCs with a different set of characteristics.

Methods of assessing watershed characteristics that are needed for certain applications are presented in the context of those applications in this book. A discussion of tools and emerging technologies for making hydrologic and watershed assessments is presented in Chapter 16.

Integrated Watershed Management

IWM involves an array of vegetative (nonstructural) and engineering (structural) practices (Gregersen et al., 2007). Soil conservation practices, constructing dams, and establishing protected reserves can be tools employed in IWM as can be land-use planning that entails developing regulations to guide timber-harvesting operations, road-building activities, urban development, and so forth. The unifying focus in all cases is placed on how these varying activities affect the relationships among land, water, and other natural resources on a watershed. The common denominator or the integrating factor is water. This focus on