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.

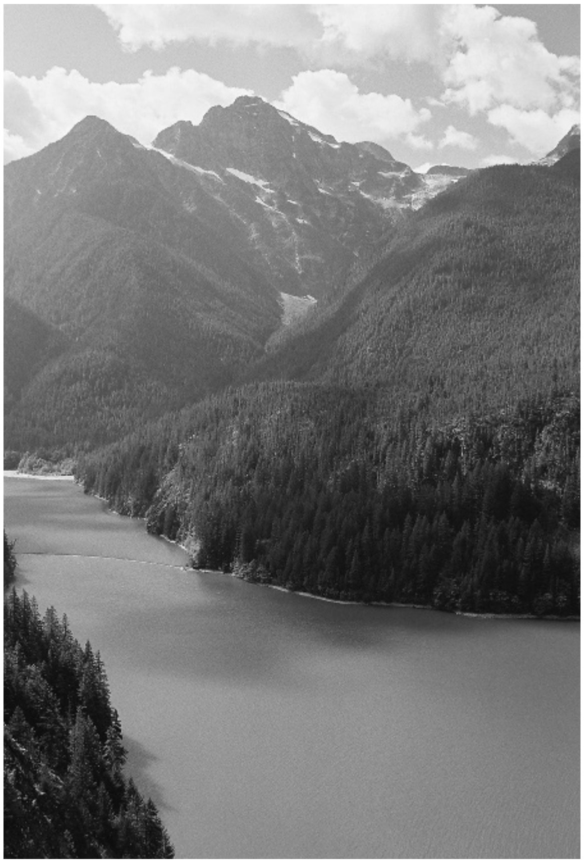

PHOTO 2. Forested headwater watersheds are the source of most of the streamflow in the United States as depicted in this scene in the Northern Cascades of Washington (Photograph by Mark Davidson) (For a color version of this photo, see the color plate section)

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

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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 waterborne 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

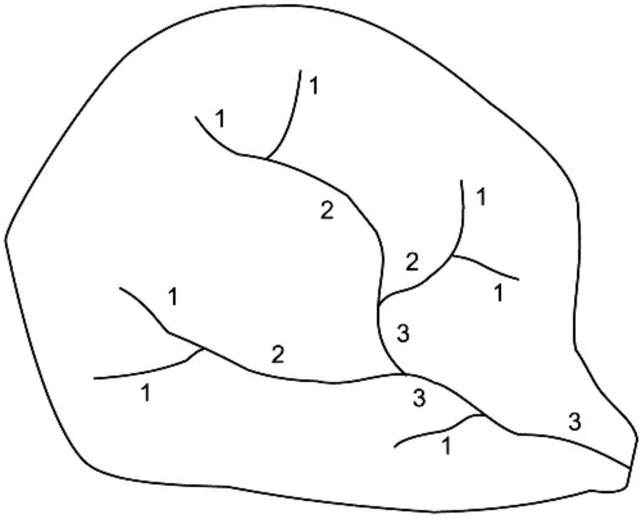

FIGURE 1.1. Stream order system by Horton (1945) as modified by Strahler (1964)

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

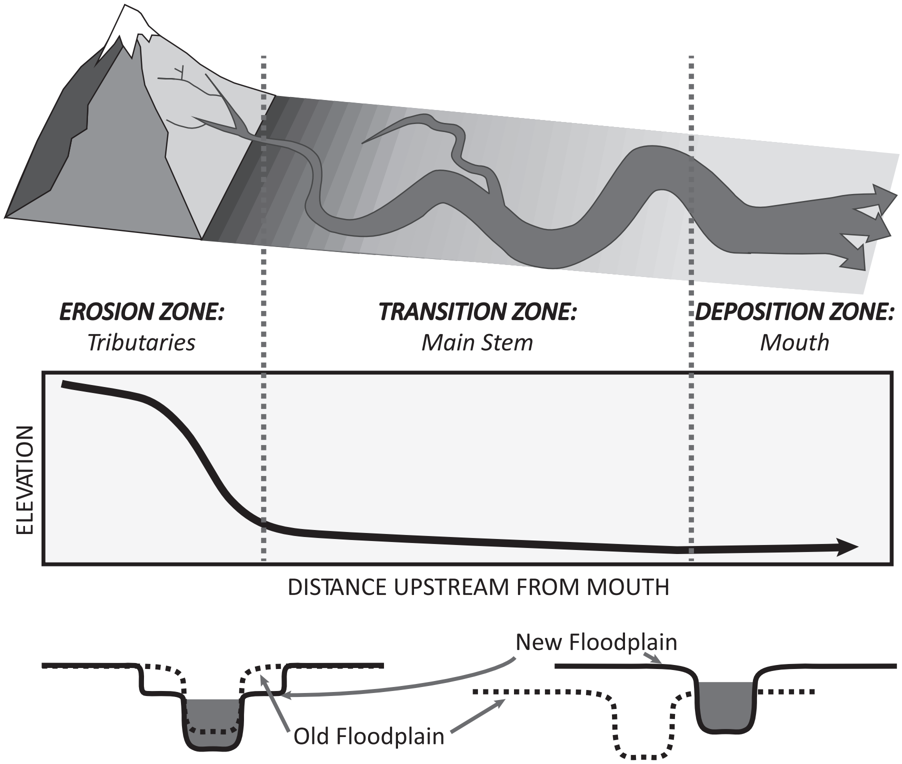

FIGURE 1.2. Rivers generally flow from an upper, high-gradient erosion zone through a transition zone to a low-gradient deposition zone (Schumm, 1977, as modified by Verry, 2007)

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 water and its interrelationship with land and other natural resources and their use is what distinguishes IWM from other natural resource management strategies.

On the one hand, IWM is an integrative way of thinking about people's activities on a watershed that have effects on, or are affected by, water. On the other hand, IWM includes tools or techniques such as the physical, regulatory, or economic means for responding to problems or potential problems involving the relationship between water and land uses. What sometimes confuses people is the fact that these tools and techniques are employed not only by those designated as "watershed managers" but also by foresters, farmers, soil conservation officers, engineers, and so forth. In reality, all are watershed managers.

This fact is both the dilemma and the strength of watershed management. In practice, activities using natural resources are decided on and undertaken by individuals, local governments, and various groups that control land in a political framework that has little relationship to, and often ignores, the boundaries of a watershed. For example, forested headwater areas of a river basin could be under the control of a governmental forestry agency but the middle elevations and lowlands could be a composite of private, municipal, and individual ownerships.

Activities are often undertaken independently with little regard to how they affect other areas. Despite this real world of disaggregated and independent political and economic actions, it remains a fact that water and its constituents flow from higher to lower elevations according to watershed boundaries, regardless of the political boundaries. What one person or group does upstream can affect the welfare of those downstream. Somehow, the physical facts of watersheds and the political realities have to be brought together to achieve IWM. Within this broad focus there is concern with both how to prevent deterioration of an existing sustainable and productive relationship between the use of land, water, and other natural resources and how to restore or create such a relationship where it has been damaged or destroyed in the past.

Embodied in IWM are

- preventive strategies aimed at preserving existing sustainable land-use practices; and
- restorative or rehabilitation strategies designed to overcome identified problems or improve conditions to a desirable level where *desirable* is defined in ecological, environmental, and political terms.

Both strategies respond to the same types of problems. However, in one case the objective is to prevent a problem from occurring while in the other case the objective is to improve conditions once the problem has occurred. In reality, we are dealing with a continuum from regulatory support and reinforcement of existing sustainable land-use practices (preventive strategy) to such actions as emergency relief, building of temporary water-control structures, restoring wetlands, or changing land use on fragile and eroded lands (rehabilitation strategy). These routine preventive strategies and actions are as important as the more dramatic and visible restorative actions. Losses avoided through preventive strategies are as important to people as gains from rehabilitating a degraded watershed. In economic terms, the cost of preventing losses of productivity in the first place can be much lower than the cost of achieving the same benefit through more dramatic actions to restore productivity on degraded lands.

SUSTAINABLE USE AND DEVELOPMENT OF NATURAL RESOURCES

There are many examples of the need to manage watersheds better to meet current and future demands for water and other natural resources in a more sustainable manner. It must be recognized, however, that practices relating to resource use and management do not depend solely on the physical and biological characteristics of watersheds. Institutional, economic, and social factors such as the cultural background of rural populations and the nature of governments need to be fully integrated into solutions that meet environmental, economic, and social objectives (Gregersen et al., 2007). How these factors are interrelated can best be illustrated by looking at specific issues.

Land and Water Scarcity

Arable land and water resources are becoming scarcer with the earth's expanding population of people. These scarcities and the human responses to these scarcities pose challenges to sustainable development and can have serious environmental consequences. Changing climatic conditions and weather patterns add uncertainty to future land and water resource management. It is unclear where and how much the supplies of freshwater will change with changes in climate and weather. What is clear, however, is that the increasing water demands caused by increasing populations of people and expanding economic developments will pose far greater problems by the year 2025 than currently (Vorosmarty et al., 2000).

Knowledge, information, and technologies will no doubt expand our capability to deal with shortages of resources. To harness these capabilities, however, will require an integrated and interdisciplinary approach to planning and managing natural resources. The lack of such an approach has been problematic as emphasized by Falkenmark (1997) who stated, "In environmental politics, land and water issues are still seen as belonging to different worlds, taken care of by different professions with distinctly different education and professional cultures." Land, water, and other natural resources have traditionally been managed in isolation of one another as a consequence. However, we recognize that land-use affects the quantity and quality of water flow in a watershed. Water development, conversely, affects land use. Understanding these relationships and linkages is essential to achieving sustainable use and development of natural resources.

Land Scarcity

Land scarcity has been exacerbated in many developing countries by the rural poor who clear forests to grow agricultural crops, cultivate steep uplands, and overgraze fragile rangelands to meet their food and natural resource needs. Watershed degradation frequently results, further reducing land productivity that in turn causes more extensive and intensive land use. In other instances, irrigation practices intended to expand agricultural productivity have been inappropriate and have caused land productivity to diminish through salinization. As watershed conditions deteriorate, the people living in both uplands and downstream areas become impacted. This cycle of deteriorating land productivity is a clear indicator of nonsustainable land use.

Of the 8.7 billion ha of agricultural land, forests, woodlands, and rangelands worldwide, almost 25% has been degraded since the mid-1900s with 3.5% being severely degraded

(Scherr and Yadav, 1996). Problems of desertification have received global attention as the productivity of some of the poorest countries in the world continues to decline. Ironically, we have the know-how to manage resources in a sustainable manner. What is most often lacking are the policies and institutions to promote and sustain sound resource use.

Water Scarcity

Water scarcity has attracted attention globally and is considered the major environmental issue facing the twenty-first century. The United Nations commemorated a World Day for Water in March 2001 where speakers concluded that demands for freshwater exceeded supplies by 15–20% and that two-thirds of the world's population will experience severe water shortages in the next 25 years. Although the 9000–14,000 km^3 of freshwater on earth should be sufficient to support expanding human populations for the foreseeable future, unequal distribution results in water scarcity (Rosegrant, 1997). For example, per capita freshwater supplies in Canada are approximately 120,000 m^3 compared to Jordan's 300 m^3. In China, per capita freshwater supplies are 2700 m^3 with 600 of its major cities suffering from water shortages. Although China encompasses the Yangtze River, the third largest river in the world, water scarcity is pronounced in areas north of the river which represent 63.5% of the country's land area but only 19% of its water resources. To enhance water supply in northern China, where more than one-third of the county's population lives, the largest water diversion project is underway to divert 44.8 billion m^3 of water annually from the Yangtze, Huaihe, and Haine rivers in the south to the drier north (www.water.technology.net/projects/south_north/). Other diversions are planned for western regions of the country.

Such programs have dramatic effects on land and water, placing greater importance on improved watershed planning and management to protect the life of major reservoir and diversion investments. The fact is that water has become a global environmental priority, exceeding climate change according to a GlobeScan/Circle of Blue Report (Box 1.2). Examples of the role of IWM in coping with water scarcity and other natural resource issues are outlined in Table 1.1.

UNESCO (www.unesco.org, 2011) estimates that global water withdrawals have tripled over the past 50 years. The International Water Management Institute (IWMI) paper of 2007 (www.iwmi.cgiar.org) reported that much of the increased use of water is attributed to irrigation of agricultural lands. Competition for water between agricultural and other interests (municipal and environmental) will undoubtedly increase in coming decades with the world's population projected to grow to 9 billion people by 2050.

Coping with Hydrometeorological Extremes

Floods, landslides, and debris torrents that result from excessive precipitation events and the droughts that result from deficient precipitation represent both dimensions of hydrometeorological extremes. The disasters and famine that can result present some of the greatest challenges to land and water resource managers. Even though we call them extreme events, it should be recognized that floods and droughts occur naturally and are not necessarily rare. However, forecasting when and where they will occur and at what magnitude is uncertain. Whether these hydrometeorological extremes end up as disasters depends on their impacts on people and natural ecosystems. What can be done to cope better with such extreme

Table 1.1. **The role of watershed management in developing solutions to natural resource problems**

Problem	Possible alternative solutions	Associated watershed management objectives
Deficient water supplies	Reservoir storage and water transport	Minimize sediment delivery to reservoir site; maintain watershed vegetative cover
	Water harvesting	Develop localized collection and storage facilities
	Vegetative manipulation; evapotranspiration reduction	Convert from deep-rooted to shallow-rooted species or from conifers to deciduous trees
	Cloud seeding	Maintain vegetative cover to minimize erosion
	Desalinization of ocean water	Not applicable
	Pumping of deep groundwater and irrigation	Management of recharge areas
Flooding	Reservoir storage	Minimize sediment delivery to reservoir site; maintain watershed vegetative cover
	Construct levees, channelization, etc.	Minimize sediment delivery to downstream channels
	Floodplain management	Zoning of lands to minimize human activities in flood-prone areas; minimize sedimentation of channels
	Revegetate disturbed and denuded areas	Plant and manage appropriate vegetative cover
Energy shortages	Utilize wood for fuel	Plant perpetual fast-growing tree species; maintain productivity of sites; minimize erosion
	Develop hydroelectric power project	Minimize sediment delivery to reservoirs and river channels; sustain water yield
Food shortages	Develop agroforestry	Maintain site productivity; minimize erosion; promote species compatible with soils and climate of area
	Increase cultivation	Restructure hillslopes and other areas susceptible to erosion; utilize contour plowing, terraces, etc.
	Increase livestock production	Develop herding–grazing systems for sustained yield and productivity
	Import food from outside watershed	Develop forest resources for pulp, wood, wildlife products, etc., to provide economic base
Erosion/sedimentation from denuded landscapes	Erosion control structures	Maintain life of structures by revegetation and management
	Contour terracing	Revegetate, mulch, stabilize slopes and institute land-use guidelines
	Revegetate	Establish, protect, and manage vegetative cover until site recovers

TABLE 1.1. (*Continued*)

Problem	Possible alternative solutions	Associated watershed management objectives
Poor-quality drinking water	Develop alternative supplies from wells and springs	Protect groundwater from contamination
	Treat water supplies	Filter through wetlands or upland forests
Polluted streams/ reduced fishery production	Control pollutants entering streams	Develop buffer strips along stream channels; maintain vegetative cover on watersheds; develop guidelines for riparian zones
	Treat wastewater	Use forests and wetlands as secondary treatment systems for wastewater

events is a critically important question that planners and managers as well as students of hydrology and watershed management should be prepared to address.

Floods, landslides, and debris torrents result in billions of dollars being spent globally each year for flood prevention, flood forecasting, and stabilization of hillslopes and stream channels. However, the cost of lives and property damage due to floods, landslides, and debris flows is staggering. The impacts of these naturally occurring phenomena can be exacerbated by human encroachment on floodplains and other hazardous areas, which is often the result of land scarcity.

Responses to disasters caused by too much water from flooding or too little water that results from droughts are most often short term and limited to helping those who have been directly impacted rather than dealing with the causes. Interest in coping with extreme events flourishes immediately after they have taken their toll on human lives and property but becomes lower priority with reduced funding as memories fade with time. The term *crisis management* captures this approach. It is not unreasonable to ask the question: what (if anything) can be done to prevent such disasters? There is no single approach that applies to all situations. To paraphrase Davies (1997), there are essentially three options available to reduce or prevent disasters caused by excessive amounts of water. These options are modifying the natural system, modifying the human system of behavior, and some combination of these two.

It is important to recognize that no matter how advanced our technologies might become, the degree to which such events result in disasters is largely because of the behavior of people on watersheds. Nevertheless, while solutions are not necessarily easily found, they must be based on sound hydrological principles.

Attempts to control events by modifying hydrologic and other natural systems most often entail the use of engineering measures including reservoirs, levees, and channelization aimed at controlling floods (see Table 1.1). There are increasing attempts to apply vegetative management and bioengineering measures along with structures to exert some control over extreme events. However, it is unrealistic to believe that we can mitigate the most extreme of hydrometeorological events. The development of such measures requires an understanding of natural hydrologic systems and processes, how these systems function, and how mitigation impacts other aspects of the environment.

Box 1.2

Water – The Top Global Environmental Concern?
http://www.circleofblue.org/waternews/2009/world/waterviews-water-tops-climate-change-as-global-priority/. Accessed April 7, 2010

A poll of 1000 people in each of 15 countries, including Canada, China, India, Mexico, Russia, United Kingdom, and the United States, suggested that fresh clean water has a greater impact on people's quality of life, exceeding concerns of air pollution, species extinction, loss of habitat, depletion of natural resources, and climate change. Water concerns range across the spectrum of water resources with top concerns expressed by countries as follows:

- India – lack of safe drinking water; water pollution; access to fresh clean water is highest priority; the Yamuna River is one of the most polluted waterways in the world.
- Russia – industrial water pollution of major rivers is of foremost concern.
- China – industrial pollution of the Yellow River and water scarcity plague many areas of China.
- United States – dependence on the Colorado River for irrigation in Imperial Valley and Coachella Valley of southern California has made water extremely scarce and valuable; the demise of the Salton Sea is attributed to high consumptive use and evaporation of water plus pollution from agricultural chemicals and trace metals.
- Mexico – Mexico City's supply is insufficient to meet the demands of its human population of more than 25 million; this has led to the depletion of underground aquifers and impaired waters due to human sewage.

We can view the options presented in Table 1.1 as those that attempt to move or control water and those that attempt to move or manage people on a watershed. Furthermore, some of the measures listed tend to be the responsibility of water resource organizations with an engineering bias such as governmental agencies responsible for flood control or irrigation projects, or private utilities companies responsible for hydropower. Organizations responsible for land management often have a land production–ecological viewpoint. Too often the separation of responsibilities and the lack of coordination lead to piecemeal programs that result in unwanted effects and, furthermore, do not have the long-term perspective needed to develop sustainable solutions.

While it is true that land use might not affect the magnitude of the most extreme hydrometeorological events, people's activities on a watershed and the cumulative effects of these activities determine the extent to which the events impact human life and welfare.

The reliance on large-scale engineering structures to store or divert water with the intention of meeting water management objectives has been met with objections from environmental groups for some time. However, there is concern by some professionals that an over-reliance on engineering measures such as dams, levees, or stream channelization has

- led to unintended and unwanted effects;
- reduced the hydrologic function and environmental values associated with natural rivers, floodplains, and estuaries; and
- imparted a false sense of security to those living in downstream areas.

Agricultural expansion and urban development have further reduced natural riparian communities, wetland ecosystems, and floodplains with often serious consequences (Box 1.3).

Box 1.3

Effects of Altering Natural Ecosystems on Flooding: Examples in the Upper Midwest, United States

The aftermath of record flooding in the upper Mississippi River in 1993 and 2001, and the 1997, 2001, 2007, and 2010 floods in the Red River of the North along the Minnesota–North Dakota boundary, led to questions concerning the extent to which the floods were the result of human modifications of watersheds. Since the beginning of the twentieth century, efforts designed largely to expand farmland have resulted in extensive drainage of wetlands and the use of tile drains on croplands. Flood control has involved levee construction and channelized rivers, with a resulting loss of floodplain storage and riparian forests.

Following the 1993 Mississippi River flood that caused $10 billion in damage (Tobin and Montz, 1994), Leopold (1994) found that in several locations the levees caused river stages to be higher than they would have been without levees being in place. As long as levees did not fail or were breached, the increased height of flood stages was retained within the channel system. However, many levees were breached, causing greater devastation than would have otherwise occurred without levees. The cumulative loss of wetland and floodplain storage along channels and in upper watersheds could have exacerbated flooding in many locations. The question of the extent to which land use and channel modifications have affected the magnitude of floods throughout the Mississippi River and the Red River of the North is uncertain. A better understanding of cause-and-effect relationships is needed; this book provides the background to help understand and address these issues.

WATERSHEDS, ECOSYSTEM MANAGEMENT, AND CUMULATIVE EFFECTS

Taking a watershed perspective has utility in addressing the many natural resource issues that span decades and involve varying climatic and land-use changes. The merit in taking a watershed perspective is clear when dealing with issues of water supply and events such as floods and droughts (see Table 1.1). Not so obvious are the effects that become compounded spatially and temporally and that at first glance might not appear to be related to hydrologic processes.

During the past century in the United States, vegetation and land-use changes on the landscape have dramatically altered the hydrologic characteristics of watersheds. Since the earliest European settlers, extensive areas of native forests and grasslands have been converted to agricultural cropland. Urban areas and road systems have expanded, riparian corridors altered, wetlands drained, and natural river systems modified. These landscape changes have resulted in hydrologic changes through modifications of watersheds, their stream systems, and surface–groundwater linkages. Changes in water flows and water quality can affect people and ecosystems in both upstream and downstream areas.

The challenge to people living on watersheds is that of mitigating the effects of all of the changes that adversely impact human welfare and the functioning of natural ecosystems. Increased attention is being paid to maintaining or restoring natural stream-channel systems, riparian communities, wetland ecosystems, and floodplains as needed to maintain the watersheds in a good hydrologic condition. For example, Hey (2001) called for a major program to maximize the natural storage of wetlands and floodplains and minimize conveyance in the upper Mississippi River Basin. Such a program would in effect reverse some of the effects of the past 200 years of levee construction and other engineering practices in the basin.

The role of watersheds as units for ecosystem management and analysis has gained international recognition in the past decades. *Ecosystem management*, a focus of natural resource management in the 1990s, is based on maintaining the integrity of ecosystems while sustaining benefits to human populations. The usefulness of a watershed approach in ecosystem management became apparent in the United States with the attempts to reconcile conflicts over the use and management of land and water in the Pacific Northwest (Montgomery et al., 1995). Environmental, economic, and political conflicts involving the use of old-growth forests for both spotted owl habitats and the production of timber were heated in this region. At the same time, concern over the effects of timber harvesting and hydropower dams on native salmon emerged. A watershed analysis approach facilitated the examination of the interrelationships between land and water use and many of the environmental effects. This approach was taken in the Pacific Northwest because watersheds define “basic, ecologically, and geomorphologically relevant management units” and “watershed analysis provides a practical analytical framework for spatially-explicit, process oriented scientific assessment that provides information relevant to guiding management decisions” (Montgomery et al., 1995, p. 371).

Cumulative watershed effects are the combined environmental effects of activities in a watershed that can adversely impact beneficial uses of the land (Reid, 1993; Sidle, 2000). The viewpoint taken here is that there are interactions among different land-use activities and there can be incremental effects that can lead to more serious overall impacts when added to past effects. Individually, these environmental effects might not appear to be relevant but collectively they can become significant over time and space. For example, the conversion from forest to agricultural cropland on one part of a watershed can cause an increase in water and sediment flow. Road construction and drainage can have similar effects elsewhere in a watershed as can the drainage of a wetland at another location.

These activities are likely to occur over a long period and, incrementally, have little obvious effect. At some point in time, however, the increased streamflow discharge in combination with additional sediment loads can lead to more frequent flooding. River channels can adjust to these changes in the flow of water and sediment to cause additional impacts downstream. These same changes can alter aquatic habitats. A watershed perspective forces one to look at multiple and cumulative effects in a unit and attempt to identify key linkages between terrestrial and aquatic ecosystems.

RECONCILING WATERSHED AND POLITICAL BOUNDARIES

Historically, land, water, and other natural resources have been managed not only by people with different technical backgrounds but also by organizations that have very focused and different missions that impact one another. There are often overlapping responsibilities. In contrast, it is rare to find organizations that have the explicit mission of watershed management. There are few organizations with responsibilities that coincide with watershed boundaries as a result. However, there is a need to cope with issues that arise between upstream and downstream entities. In response to these needs, watershed management organizations and institutions have emerged with responsibilities of planning and managing resources to resolve upstream–downstream conflicts that arise (see NRC, 2000).

Locally led watershed management organizations and initiatives have been established under various names, including watershed associations, partnerships, councils, and other "co-management" schemes administered jointly by governments and local communities. They all emphasize the growing awareness of the important hydrologic linkages between uplands and downstream areas. Furthermore, there is a growing recognition that institutional arrangements and supportive policies are needed so that people can develop sustainable solutions to land and water problems and avoid land and water degradation. By the late 1990s, more than 1500 locally led initiatives were established in the United States in response to water resource problems that were not being addressed (Lant, 1999). These initiatives were largely in response to the issues discussed above, including the effects of urbanization, intensification of agriculture, forest management activities, stream channelization, and wetland drainage on flooding, water yield, and water quality.

A river basin management strategy has emerged in North Carolina, United States (www.ncwater.org/basins, accessed May 24, 2011), as a result of a decade of water supply demands exceeding water supplies in many locations of the state. Water shortages during a 4-year drought intensified in 2002, suggesting that actions would be needed to avoid adverse economic impacts caused by insufficient water supplies. The river basin strategy took the approach that river basins provide the fundamental units for local and state governmental organizations to monitor water availability and use and to facilitate planning to develop 50-year water supply plans to solve water supply problems. A similar strategy, but for

Box 1.4

Minnesota's Major Watershed Restoration and Protection Strategy

In November of 2008 after the US stock market crashed and votes throughout the United States sent Barack Obama to Washington DC, Minnesotans voted to raise their sales tax by 3/8's of a percent. A new clean water and land legacy fund was created to clean up the state's impaired waters and preserve valued hunting land and wetlands over a 25-year period. The state developed a strategy for not only restoring impaired waters, but also identifying land at risk of developmental changes that could adversely impact water resources in the future. The strategy focused on several key areas:

(1) Assess the overall condition and health of the many lakes, streams, rivers, wetlands by major watersheds using biological metrics in the form of an Index of Biological Integrity (IBI). A major watershed is defined as an eight-digit HUC according to the U.S. Geological Survey; Minnesota has 81.
(2) Develop an assessment document, including additional data such as Lake Secchi, Chlorophyll A, and total Phosphorus that would guide listings for the Section 303(d) list of the Clean Water Act.
(3) Conduct a Stressor Identification analysis to validate true water quality impairment. This step involves more than examining toxic influences upon fish; hydrologic, geologic, geomorphic, and connectivity data must be gathered to define natural background and superimposed anthropogenic activity.
(4) Construct computer models for each major watershed to help manage current land-use conditions and predict future water quality scenarios based on climate and land-use change.
(5) Perform statistical analysis and synthesis of all data and model results to identify Priority Management Zones for restoration or protection action.
(6) Lastly, with Clean Water Legacy funds implement Best Management Practices where they are most needed on the landscape to form watershed-based treatment trains from upland through riparian and into channels, lakes, and wetlands.

This approach is unique in the United States; no other state has this level of local funding focused on an IWM approach (www.pca.state.mn.us/index.php/view-document.html?gid = 14224).

different purposes, has been developed in Minnesota where major watersheds are used as the units of management to meet water quality objectives (Box 1.4).

Institutional responses to international water issues are also emerging. For example, transboundary issues in the Nile River Basin have focused attention on watersheds as a logical framework for analysis and understanding of the effects of human actions in one part of the basin on those living downstream. Here, concerns about water, human poverty, biodiversity, and wildlife are paramount. The disparity between watershed and political boundaries prompted the Nile Basin Initiative and an extensive study into transboundary issues of the Nile River Basin (Box 1.5). The inequities in rainfall and water supply among the ten riparian countries of the Nile River Basin have threatened sustainable development in the region and have historically resulted in political conflict (Baecher et al., 2000). While a necessary and daunting task, developing solutions to water supply problems is

Box 1.5

The Nile River Basin: A Case for Watershed Management (Baecher et al., 2000)

The Nile River is the longest river of the world, traversing 6700 km from the rift valleys of East Africa, connecting with the Blue Nile from the Ethiopian highlands, and emptying into the Mediterranean Sea through the broad delta of Egypt. Annual rainfall amounts vary to the extreme within the basin. The Ethiopian highland watersheds experience more than 2000 mm of annual rainfall and contribute 60–80% of the water flow in the Nile River, yet represent less than 10% of the land area in the Nile Basin. Vast areas of the northern Basin, on the other hand, average less than 50 mm of annual rainfall. Consequently, the watersheds of Egypt and Sudan, which constitute more than 75% of the basin, contribute negligible flow to the Nile River.

Efforts to relocate waters of the Nile Basin for economic development have led to environmental concerns and potential political conflict. Lake Nassar, created by the large Aswan Dam of the lower Nile River, is essential to Egypt's economy but is vulnerable to water losses upstream. The controversial Jonglei Canal was proposed to enhance downstream water supplies by diverting water from the vast Sudd wetland to the lower and drier north – at the expense of the loss of valuable habitat. In contrast, Ethiopia as one of the poorest countries in the basin would benefit economically by expanding its irrigation and hydropower production through construction of dams in the uplands. However, such projects would meet with objections from downstream riparian countries. Furthermore, such projects, whether in uplands or lowlands, are threatened by intensive land use, watershed degradation, and deforestation that impair the quantity and quality of streamflow and aquatic habitat. Forest cover in the Ethiopian Highlands decreased from more than 15% in the 1950s to less than 4% (43.4 million ha) by 2000. FAO (2007) indicated that annual deforestation was occurring at a rate of 1410 km^2/year. Overgrazing and cultivation of hillslopes lead to soil erosion, loss of productivity of the land, and increased sediment delivery downstream. All these issues focus on the need for watershed management that extends beyond country boundaries.

not necessarily sufficient. The growth and distribution of human populations, widespread poverty, and inadequate policy responses to land and water resource issues compound problems in the basin. A major theme in the Nile Basin Initiative is that land and water must be managed in harmony so that environmental conditions and human welfare benefit. IWM is one of the key themes in this effort.

A proactive approach to IWM involves establishing and sustaining preventive practices. This approach requires instituting guidelines of land use and implementing land-use practices on a day-to-day basis that result in long-term, sustainable resource development and productivity without causing soil and water problems. Land and natural resource management agencies in the United States and many other countries have established policies that embody sound watershed management principles. These preventive measures might not make for exciting reading but in total they represent the ultimate goal of IWM. Achieving this goal requires that managers recognize the implications of their actions and that they work effectively within the social and political setting in which they find themselves.

The dilemma in watershed management is that land-use changes needed to promote the survival of society in the long term can be at cross-purposes with what is essential to the survival of the individual in the short term. Requirements for food, high-quality water, and the commodities and amenities provided by natural resources today should not be met at the expense of future generations. Therefore, any discussion of sustainable natural resource development should consider watershed boundaries, the linkages between uplands and downstream areas, and the effects of land-use practices on long-term productivity. Land use that is at cross-purposes with environmental capabilities cannot be sustained. However, sustainable productivity and environmental protection can be achieved with the integrated, holistic approach that explicitly considers hydrology and the management of watersheds.

SUMMARY AND LEARNING POINTS

Watersheds are biophysical systems that describe how units of land are connected by water flow. They also represent systems that are suitable for developing sustainable use and management of multiple resources under the tenet that land and water should be managed in concert with one another – the basis for IWM. This introductory chapter lays out the reasons for taking an IWM approach – which the reader should be able to understand – as well as the role of IWM in coping with land and water scarcity and hydrometeorological extremes.

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