CHAPTER 1

Introduction

1.1 Water-Resources Engineering

Water-resources engineering is concerned with the analysis and design of systems to control the quantity, quality, timing, and distribution of water to meet the needs of human habitation and the environment. Aside from the engineering and environmental aspects of water-resource systems, their feasibility from legal, economic, financial, political, and social viewpoints must also be considered in the development process. In fact, the successful operation of an engineered system usually depends as much on nonengineering analyses (e.g., economic and social analyses) as on sound engineering design (Delleur, 2003); this is particularly true in developing countries (Brookshire and Whittington, 1993). Examples of water-resource systems include domestic and industrial water supply, wastewater treatment, irrigation, drainage, flood control, salinity control, sediment control, pollution abatement, and hydropower-generation systems.

The waters of the earth are found on land, in the oceans, and in the atmosphere. The core science of water-resources engineering is *hydrology*, which deals with the occurrence, distribution, movement, and properties of water on earth. Engineering hydrologists are primarily concerned with water on land and in the atmosphere, from its deposition as atmospheric precipitation, such as rainfall and snowfall, to its inflow into the oceans and its vaporization into the atmosphere. The technical areas that are fundamental to water-resources engineering can be grouped into the following five categories:

1. Subsurface hydrology
2. Surface water and climate
3. Hydrogeochemistry and water chemistry
4. Erosion, sedimentation, and geomorphology
5. Water policy, economics, and systems analysis

Subsurface hydrology is concerned with the occurrence and movement of water below the surface of the earth; surface water and climate studies are concerned with the occurrence and movement of water above the surface of the earth; hydrogeochemistry is concerned with the chemical changes in water that is in contact with earth materials; erosion, sedimentation, and geomorphology deal with the effects of sediment transport on landforms; and water policy, economics, and systems analyses are concerned with the political, economic, and environmental constraints in the design and operation of water-resource systems. The quantity and quality of water are inseparable issues in design, and the modern practice of water-resources engineering demands that practitioners be technically competent in understanding the physical processes that govern the movement of water, the chemical and biological processes that affect the quality of water, the economic and social considerations that must be taken into account, and the environmental impacts associated with the construction and operation of water-resource projects.

The design of water-resource systems usually involves interaction with government agencies. Collection of hydrologic and geologic data, granting of development permits, specification of design criteria, and use of government-developed computer models of water-resource systems are some of the many areas in which water-resource engineers interact with government agencies. The following are some of the key water-resources agencies in the United States:

- **U.S. Geological Survey (USGS).** The Water Resources Division of the USGS has primary federal responsibility for collection and dissemination of measurements of stream discharge and stage, reservoir and lake stage and storage, ground-water levels, well and spring discharge, and the quality of surface and ground water in the United States. USGS maintains a network of thousands of stream gages and ground-water monitoring wells. Most of this data can be accessed using the National Water Information System II at the Web site `waterdata.usgs.gov/nwis/`. USGS constructs and distributes $7\frac{1}{2}$-minute quadrangle topographic maps, which are useful in hydrologic studies; the agency also produces geological maps of subsurface formations.
- **National Climatic Data Center (NCDC).** NCDC, the world's largest active source of weather data, produces numerous climate publications and responds to data requests from all over the world. Most of the data available from NCDC is collected and analyzed by the National Weather Service (NWS), Military Services, Coast Guard, Federal Aviation Administration, and cooperative observers. Data collected by NWS include rainfall and evaporation measurements at over 10,000 locations in the United States.
- **U.S. Bureau of Reclamation (USBR).** USBR is responsible for planning, construction, operation, and maintenance of a variety of water-resource facilities whose objectives include irrigation, power generation, recreation, fish and wildlife preservation, and municipal water supply. Most activities are confined to the 17 states west of the Mississippi River. Besides being the largest wholesale supplier of water in the United States, USBR is the sixth largest hydroelectric supplier in the United States.
- **U.S. Environmental Protection Agency (USEPA).** USEPA is responsible for the implementation and enforcement of federal environmental laws. The agency's mission is to protect public health and to safeguard and improve the natural environment—air, water, and land—upon which human life depends.
- **U.S. Natural Resources Conservation Service (NRCS).** NRCS, formerly the Soil Conservation Service, works with landowners on private lands to conserve natural resources. NRCS provides technical and financial assistance to farmers and ranchers for flood protection, recreation, and water-supply development in small watersheds (less than 100,000 ha). The NRCS publishes general soil maps for each state and detailed soil maps for each county in the United States.
- **U.S. Army Corps of Engineers (USACE).** USACE is responsible for the planning, construction, operation, and maintenance of a variety of water-resource facilities whose objectives include navigation, flood control, water supply, recreation, hydroelectric power generation, water-quality control, and other purposes.

TABLE 1.1: Selected Internet Sites Relevant to Water-Resources Engineering in the United States

Organization	Web address
National Climatic Data Center (NCDC)	www.ncdc.noaa.gov
U.S. Army Corps of Engineers (USACE)	www.usace.army.mil
U.S. Bureau of Reclamation (USBR)	www.usbr.gov
U.S. Environmental Protection Agency (EPA)	www.epa.gov
U.S. Geological Survey (USGS)	www.usgs.gov
U.S. Natural Resources Conservation Service (NRCS)	www.nrcs.usda.gov

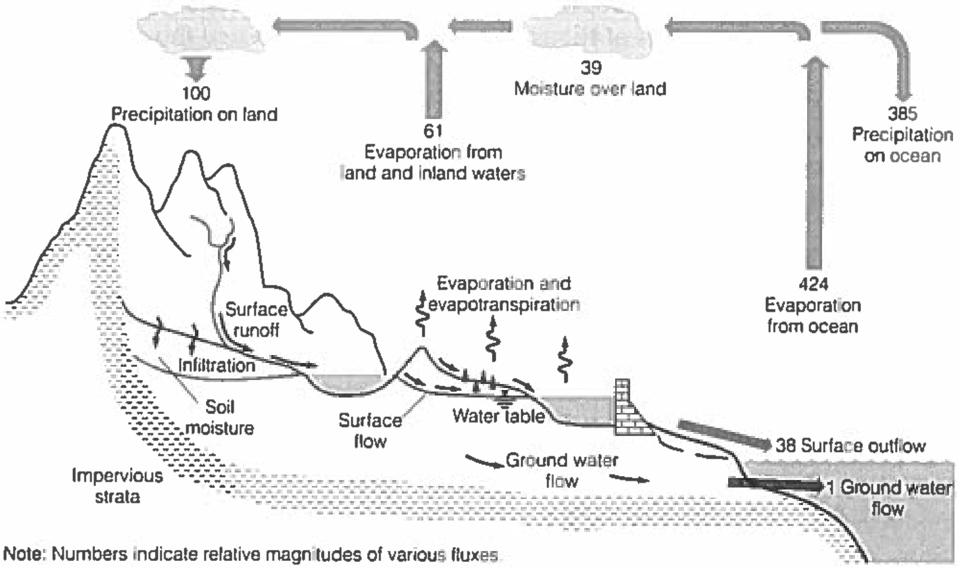
These government agencies provide a wealth of information on water resources, relevant government regulations, and useful computer software that can be found on the internet. Several of the more useful Web sites currently in use (and likely to be around for the foreseeable future) are listed in Table 1.1.

1.2 The Hydrologic Cycle

The *hydrologic cycle* is defined as the pathway of water as it moves in its various phases through the atmosphere, to the earth, over and through the land, to the ocean, and back to the atmosphere (National Research Council, 1991). The movement of water in the hydrologic cycle is illustrated in Figure 1.1, where the relative magnitudes of various hydrologic processes are given in units relative to a value of 100 for the rate of precipitation on land. The relative magnitudes are based on global annual averages (Chow et al., 1988).

A description of the hydrologic cycle can start with the evaporation of water from the oceans driven by energy from the sun. The evaporated water, in the form of water vapor, rises by convection, condenses in the atmosphere to form clouds, and precipitates onto land and ocean surfaces, predominantly as rain or snow. Precipitation on land surfaces is partially intercepted by surface vegetation, partially stored in surface

FIGURE 1.1: Hydrologic cycle. Source: Chow et al. (1988).



Note: Numbers indicate relative magnitudes of various fluxes depressions, partially infiltrated into the ground, and partially flows over land into drainage channels and rivers that ultimately lead back to the ocean. Precipitation that is intercepted by surface vegetation is eventually evaporated into the atmosphere; water held in depression storage either evaporates or infiltrates into the ground; and water that infiltrates into the ground contributes to the recharge of ground water, which either is utilized by plants or becomes subsurface flow that ultimately emerges as recharge to streams or directly to the ocean. *Ground water* is defined as the water below the land surface; water above the land surface (in liquid form) is called *surface water*. In urban areas, the ground surface is typically much less pervious than in rural areas, and surface runoff is mostly controlled by constructed drainage systems. Surface waters and ground waters in urban areas also tend to be significantly influenced by the water-supply and wastewater removal systems that are an integral part of urban developments. Since humanmade systems are part of the hydrologic cycle, it is the responsibility of the water-resources engineer to ensure that systems constructed for water use and control are in harmony with the needs of the natural environment.

The quality of water varies considerably as it moves through the hydrologic cycle, with contamination resulting from several sources. Classes of contaminants commonly found in water, along with some examples, are listed in Table 1.2. The effects of the quantity and quality of water on the health of terrestrial ecosystems and the value of these ecosystems in the hydrologic cycle are often overlooked. For example, the modification of free-flowing rivers for energy or water supply, and the drainage of wetlands, can have a variety of adverse effects on aquatic ecosystems, including losses in species diversity, floodplain fertility, and biofiltration capability (Gleick, 1993).

On a global scale, the distribution of the water resources of the earth is given in Table 1.3, where it is clear that the vast majority of the earth's water resources is contained in the oceans, with most of the fresh water being contained in ground water and polar ice. The amount of water stored in the atmosphere is relatively small, although the flux of water into and out of the atmosphere dominates the hydrologic cycle. Wood (1991) estimated that the typical residence time for atmospheric water is on the order of a week, the typical residence time for soil moisture is on the order of weeks to months, and the typical residence time in the oceans is on the order of tens of thousands of years. The estimated fluxes of precipitation, evaporation, and runoff

TABLE 1.2: Classes of Water Contaminants

Contaminant class	Example
Oxygen-demanding wastes	Plant and animal material
Infectious agents	Bacteria and viruses
Plant nutrients	Fertilizers, such as nitrates and phosphates
Organic chemicals	Pesticides, such as DDT, detergent molecules
Inorganic chemicals	Acids from coal mine drainage, inorganic chemicals such as iron from steel plants
Sediment from land erosion	Clay silt on streambed, which may reduce or even destroy life forms living at the solid-liquid interface
Radioactive substances	Waste products from mining and processing of radioactive material, radioactive isotopes after use
Heat from industry	Cooling water used in steam generation of electricity

TABLE 1.3: Estimated World Water Quantities

Item	Volume ($\times 10^3$ km^3)	Percent total water (%)	Percent fresh water (%)
Oceans	1,338,000.	96.5	
Ground water			
Fresh	10,530.	0.76	30.1
Saline	12,870.	0.93	
Soil moisture	16.5	0.0012	0.05
Polar ice	24,023.5	1.7	68.6
Other ice and snow	340.6	0.025	1.0
Lakes			
Fresh	91.	0.007	0.26
Saline	85.4	0.006	
Marshes	11.47	0.0008	0.03
Rivers	2.12	0.0002	0.006
Biological water	1.12	0.0001	0.003
Atmospheric water	12.9	0.001	0.04
Total water	1,385,984.61	100.	
Fresh water	35,029.21	2.5	100.

Source: USSR National Committee for the International Hydrological Decade (1978).

TABLE 1.4: Fluxes in Global Hydrologic Cycle

Component	Oceanic flux (mm/year)	Terrestrial flux (mm/year)
Precipitation	1270	800
Evaporation	1400	484
Runoff to ocean (rivers plus ground water)	—	316

Source: USSR National Committee for the International Hydrological Decade (1978).

within the global hydrologic cycle are given in Table 1.4. These data indicate that the global average precipitation over land is on the order of 800 mm/yr (31 in./yr), of which 484 mm/yr (19 in./yr) is returned to the atmosphere as evaporation and 316 mm/yr (12 in./yr) is returned to the ocean via surface runoff. On a global scale, large variations from these average values are observed. In the United States, for example, the highest annual rainfall is found at Mount Wai'ale'ale on the Hawaiian island of Kauai with an annual rainfall of 1168 cm (460 in.), while Greenland Ranch in Death Valley, California, has the lowest annual average rainfall—4.5 cm (1.78 in.)—in the United States. Two of the most widely used climatic measures are the mean annual rainfall and the mean annual potential evapotranspiration. A *climatic spectrum* appropriate for subtropical and midlatitudinal regions is given in Table 1.5, and water-resource systems tend to differ substantially between climates. For example, forecasting and planning for drought conditions is particularly important in semiarid climates, whereas droughts are barely noticeable in very humid areas.

TABLE 1.5: Climate Spectrum

Climate	Mean annual precipitation (mm)	Mean annual evapotranspiration (mm)	Length of rainy season (months)
Superarid	<100	<3,000	<1
Hyperarid	100–200	2400–3600	1–2
Arid	200–400	2000–2400	2–3
Semiarid	400–800	1600–2000	3–4
Subhumid	800–1600	1200–1600	4–6
Humid	1600–3200	1200	6–9
Hyperhumid	3200–6400	1200	9–12
Superhumid	≥6400	1200	12

Source: Ponce et al. (2000).

On regional scales, water resources are managed within topographically defined areas called *watersheds* or *basins*. These areas are typically enclosed by topographic high points in the land surface, and within these bounded areas the path of the surface runoff can usually be controlled with a reasonable degree of coordination.

1.3 Design of Water-Resource Systems

The uncertainty and natural variability of hydrologic processes require that most water-resource systems be designed with some degree of *risk*. Approaches to designing such systems are classified as either *frequency-based design*, *risk-based design*, or *critical-event design*. In frequency-based design, the exceedance probability of the design event is selected a priori and the water-resource system is designed to accommodate all lesser events up to and including an event with the selected exceedance probability. The water-resource system will then be expected to fail with a probability equal to the exceedance probability of the design event. The frequency-based design approach is commonly used in designing the minor structures of urban drainage systems. For example, urban storm-drainage systems are typically designed for precipitation events with return periods of 10 years or less, where the *return period* of an event is defined as the reciprocal of the (annual) exceedance probability of the event. In risk-based design, systems are designed such that the sum of the capital cost and the cost of failure is minimized. Capital costs tend to increase and the cost of failure tends to decrease with increasing system capacity. Because any threats to human life are generally assigned extremely high failure costs, structures such as large dams are usually designed for rare hydrologic events with long return periods and commensurate small failure risks. In some extreme cases, where the consequences of failure are truly catastrophic, water-resource systems are designed for the largest possible magnitude of a hydrologic event. This approach is called critical-event design, and the value of the design (hydrologic) variable in this case is referred to as the *estimated limiting value* (ELV).

Water-resource systems can be broadly categorized as *water-control systems* or *water-use systems*, as shown in Table 1.6, but it should be noted that these systems are not mutually exclusive. A third category of *environmental restoration systems* has been suggested by Mays (1996). The following sections present a brief overview of the design objectives in water-control and water-use systems.

TABLE 1.6: Water-Resource Systems

Water-control systems	Water-use systems
Drainage	Domestic and industrial water supply
Flood control	Wastewater treatment
Salinity control	Irrigation
Sediment control	Hydropower generation
Pollution abatement	

1.3.1 Water-Control Systems

Water-control systems are primarily designed to control the spatial and temporal distribution of surface runoff resulting from rainfall events. Flood-control structures and storage impoundments reduce the peak flows in streams, rivers, and drainage channels, thereby reducing the occurrence of floods. A *flood* is defined as a high flow that exceeds the capacity of a stream or drainage channel, and the elevation at which the flood overflows the embankments is called the *flood stage*. A *floodplain* is the normally dry land adjoining rivers, streams, lakes, bays, or oceans that is inundated during flood events. Typically, flows with return periods from 1.5 to 3 years represent bankfull conditions, with larger flows causing inundation of the floodplain (McCuen, 1989). The 100-year flood has been adopted by the U.S. Federal Emergency Management Agency (FEMA) as the base flood for delineating floodplains, and the area inundated by the 500-year flood is sometimes delineated to indicate areas of additional risk. Encroachment onto floodplains reduces the capacity of the watercourse and increases the extent of the floodplain. Approximately 7%–10% of the land in the United States is in a floodplain, and in the 1970s flood-related deaths were 200 per year, with another 80,000 per year forced from their homes (Wanielista and Yousef, 1993).

The largest floodplain areas in the United States are in the South; the most populated floodplains are along the north Atlantic coast, the Great Lakes region, and in California (Viessman and Lewis, 1996).

In urban settings, water-control systems include storm-sewer systems for collecting and transporting surface runoff, and storage reservoirs that attenuate peak runoff rates and reduce pollutant loads in drainage channels. Urban stormwater control systems are typically designed to prevent flooding from runoff events with return periods of 10 years or less. For larger runoff events, the capacity of these systems is exceeded and surface (street) flooding usually results.

1.3.2 Water-Use Systems

Water-use systems are designed to support human habitation and include water-treatment systems, water-distribution systems, wastewater-collection systems, and wastewater-treatment systems. The design capacity of these systems is generally dictated by the population of the service area, commercial and industrial requirements, and the economic design life of the system. Water-use systems are designed to provide specified levels of service: Water-treatment systems, for example, must produce water of sufficient quality to meet drinking water standards, water-distribution systems must deliver peak demands while sustaining adequate water pressures, wastewater-collection systems must have sufficient capacity to transport wastes without overflowing into the streets, and wastewater-treatment systems must provide a sufficient level of treatment that effluent discharges will not degrade the aquatic environment. In agricultural areas, the water requirements of plants are met by a combination of rainfall and irrigation. The design of irrigation systems requires the estimation of crop evapotranspiration rates and leaching requirements in agricultural areas, with the portion of these requirements that are not met by rainfall being met by irrigation systems. In rivers where there is sufficient available energy, such as behind large dams or in rapidly flowing rivers, hydroelectric power generation may be economically feasible.

1.4 About this Book

The fundamental technical aspects of water-resources engineering derive mostly from hydraulics, hydrology, probability and statistics, and economics. A good understanding of these subject areas is the foundation on which engineers build sound designs and operational protocols for water-resource systems. This book addresses each of these fundamental areas in detail.

Chapter 2 presents the hydraulics of flow in closed conduits along with detailed coverage of the application of closed-conduit flow principles to the design of water-distribution systems. The estimation of water demand and design flows, pipeline selection, pump selection, storage-reservoir design, and estimation of service pressures are all covered. The hydraulics of flow in open channels is rigorously presented in Chapter 3, from basic principles to the computation of water-surface profiles, with design applications including hydraulic structures, channels, and sanitary-sewer systems. Chapter 4 reviews probability-distribution functions, the estimation of probability distributions from measured hydrologic data, and applications of probability and statistics to risk analysis in water-resource systems. Surface-water hydrology is presented in Chapter 5 from an urban perspective through the specification of design rainfall and abstraction models and the computation of the quantity and quality of surface runoff resulting from a specified rainfall. The design of urban stormwater-management systems is covered in detail, and the estimation of evapotranspiration, which is fundamental to the design of agricultural irrigation systems, is also covered. Chapter 6 covers the basic principles of flow in porous media, with particular emphasis on the flow fields induced by pumping wells. The fundamentals of saltwater intrusion and flow in the unsaturated zone are also covered. Design applications of ground-water hydrology include the design of municipal wellfields, the design and construction of water-supply wells, the delineation of wellhead-protection areas, the design of aquifer pumping tests, and the design of exfiltration trenches for ground-water injection. Chapter 7 describes the conventional water-resources planning process, legal and regulatory issues that must be addressed, and techniques for assessing economic feasibility. The application of water-resources planning and management to water-supply projects, floodplain management, drought management, irrigation systems, dams and reservoirs, hydropower projects, and navigation are all covered.

In summary, this book covers the subject areas that are fundamental to the practice of water-resources engineering. A firm grasp of the material covered in this book along with complementary practical experience are the foundations on which water-resources engineering is practiced.

Problems

1.1. Search the World Wide Web to determine the mean annual rainfall and evapotranspiration of Boston, Massachusetts, and Santa Fe, New Mexico. Classify the climate in these cities.