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Introduction

Water resources engineering involves people, natural resources, and constructed facilities. In meeting the water-related needs of society, water resources engineers both (1) formulate and implement resource management strategies, and (2) plan, design, construct, and operate structures and facilities. Development and management of the natural resource *water* are essential for human survival and prosperity. Water management is also integrally linked to stewardship of land and environmental resources. The water-related infrastructure of a city, region, or nation includes river regulation structures, wells for pumping groundwater, storage and conveyance facilities, treatment plants, water distribution networks, wastewater management systems, flood damage reduction measures, erosion mitigation practices, stormwater drainage systems, bridges, hydroelectric power plants, and various other constructed facilities.

1.1 WATER RESOURCES ENGINEERING DISCIPLINES

Water resources engineering is one of the several major subdisciplines of civil engineering. Civil engineers serve the public by solving problems and addressing needs related to developing/maintaining the physical infrastructure and protecting/restoring the environment. Most civil engineers deal with water problems to at least some extent throughout their professional careers. Many civil engineers specialize specifically in water resources engineering.

This book covers water management practices; hydrologic and hydraulic engineering principles; and hydrosystems planning, design, and analysis. Basic concepts of hydrology, hydraulics, and water resources systems engineering are applied to practical problems of managing water resources.

Hydrology is the study of the occurrence, distribution, movement, and properties of the waters of the earth. Engineering hydrology involves understanding hydrologic processes, data collection and analysis, mathematical modeling, and hydrologic design. Although the book devotes more attention to water quantity than water quality, both of these closely interrelated aspects of hydrology are covered.

Hydraulics is the study of the mechanical behavior of water in physical systems and processes. Hydraulics is the practical application of the principles of fluid mechanics in water resources engineering. Hydraulic analysis of natural and man-made systems and/or design of constructed facilities may involve flow through open channels, pressure conduits, and/or porous media. Sediments and other contaminants may be transported with the water.

Water resources systems engineering may be defined as the formulation and evaluation of alternative plans to determine that particular system configuration or set of actions that will best accomplish public objectives within the constraints of governing natural laws, engineering principles, economics, environmental protection objectives, social and political pressures, legal restrictions, and institutional and financial capabilities. Hydrologic and hydraulic engineering are combined with other disciplines to support analysis and decision-making processes involved in planning, designing, maintaining, and operating water management systems.

The term *hydrosystems engineering* has been used synonymously with *water resources engineering* to highlight the systems analysis perspective. The broader term *water resources planning and management* encompasses water resources engineering, but emphasizes the interdisciplinary institutional, political, and socio-economic, as well as technical engineering, aspects of the processes by which society addresses its water-related problems and needs.

Environmental engineering and *water resources engineering* are integrally connected and greatly overlapping. Both are specialty fields within civil engineering. The environmental/water resources interconnections have grown in importance over the past several decades, as the fields of *hydraulic engineering* and *sanitary engineering* grew into *water resources engineering* and *environmental engineering*, respectively. Environmental engineering is concerned with provision of safe, palatable, and ample water supplies; disposal or recycling of wastewater and solid wastes; control of water, soil, and atmospheric pollution; mitigation of the adverse social and environmental impacts of human activities; and engineering aspects of the public health field, such as sanitation, control of arthropod-borne diseases, and elimination of industrial health hazards. This book omits water-related subjects such as water and wastewater treatment that are covered in depth by environmental engineering textbooks. However, all of the material presented in this book is relevant to environmental engineers.

The book is written by civil engineers for civil engineers. However, water resources development and management are interdisciplinary in nature. Water-related needs and issues are broad, complex, and crucial to economic/social development and environmental protection. Consequently, water resources engineers work with political officials, economists, lawyers, urban planners, agricultural scientists, chemists, biologists, geologists, meteorologists, computer analysts, and professionals from various other scientific and engineering disciplines, as well as water users and the public.

1.2 WATER MANAGEMENT SECTORS

Water management involves the development, control, regulation, protection, and beneficial use of surface and groundwater resources. Water management activities include policy formulation; national, regional, and local resource assessments; regulatory and permitting functions; formulation and implementation of resource management strategies; planning, design, construction, maintenance, rehabilitation, and operation of structures and facilities; scientific and engineering research; and education and training.

Water is essential to all of us. Human health and socioeconomic welfare is dependent on adequate supplies of suitable quality water. Conversely, too much water results in socioeconomic damages and loss of life due to flooding. Flood mitigation, stormwater management, and erosion control are important concerns in water resources engineering. The vitality of natural ecological systems is dependent on mankind's stewardship of water resources. Water management has played a key

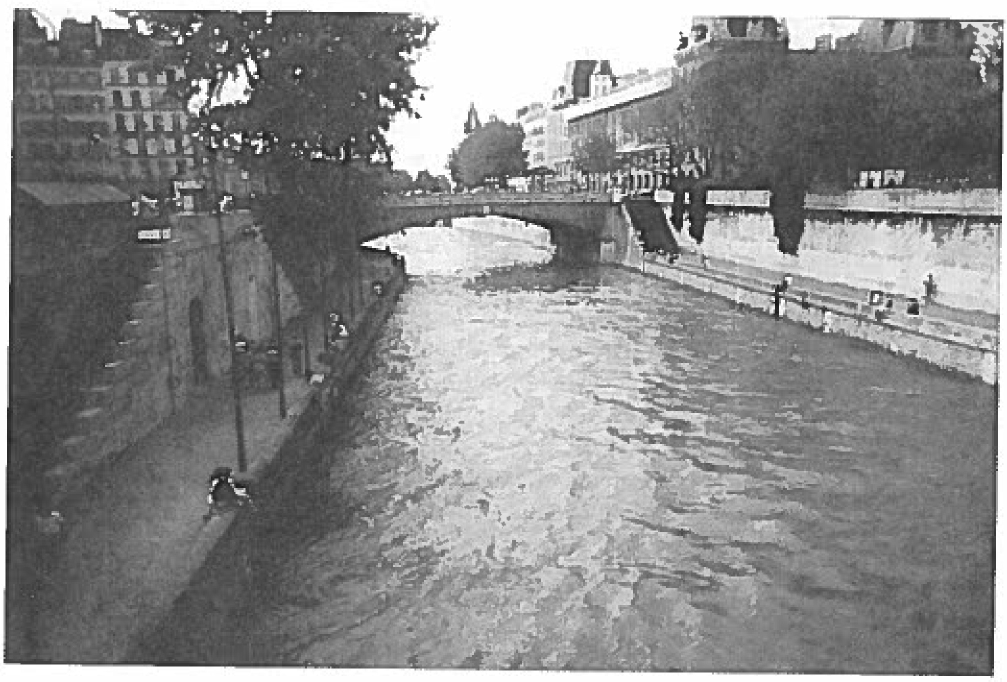

Figure 1.1 The Seine River flowing through Paris is illustrative of the propensity for cities to develop adjacent to streams and rivers. (Photo by R. A. Wurbs, June 1996)

Figure 1.2 The London docks extend along 56 km of the 340-km Thames River. The river is the main water supply source for London. (Photo by R. A. Wurbs, May 1998)

role in the development of civilizations since ancient times. Population growth, urban and industrial development, and expansion of irrigated agriculture have resulted in drastically increased demands and problems during the past century.

The 1940's–1980's were the construction era of water resources development in the United States. Numerous multipurpose dams, hydropower plants, flood control improvements, navigation facilities, and irrigation projects were designed and constructed during the 1940's–1970's. The 1970's–1980's were a peak period for construction of wastewater treatment plants. Construction of new facilities continues to be important today. However, water resources management policy and practice shifted during the 1970's–1980's to major emphases on (1) maintenance, rehabilitation, and operation of the massive inventory of existing facilities, and (2) nonstructural strategies for managing water and related land resources. Protection and restoration of water quality and environmental resources have also been driving concerns since the 1970's.

The scale and complexity of water resources engineering projects vary greatly. For example, an engineer may design a culvert for a road construction project to convey rainfall runoff from a watershed with a drainage area of less than a square kilometer. Other engineers may be conducting studies to optimize the operations of a major multiple-purpose, multiple-reservoir system regulating stream flows of an interstate river basin with a watershed area of many thousand square kilometers. From the perspective of the citizens of a small community, a local groundwater aquifer contained completely within their county is of the utmost importance because it provides their domestic water supply. However, the pumpage from the few wells in this relatively small aquifer is a minute fraction of the volume of water pumped from the High Plains Ogallala Aquifer that extends across seven states, from South Dakota to northern Texas, with economies highly dependent on irrigated agriculture. The scale and complexity of construction projects range from a small pipeline extending water supply services to several new residential homes to dams and appurtenant structures that are among the largest engineering projects ever constructed.

Although water resources engineering projects often focus on a single purpose, multiple-purpose development is also common. The important concept of multiple-purpose water management is illustrated by a reservoir system that stores flood waters that are later released through hydroelectric power turbines and diverted further downstream for municipal and industrial water supply while ensuring adequate instream flows to maintain fisheries and wildlife habitat. An athletic field in a neighborhood park may be used as a stormwater detention basin. Detention storage may provide sediment and water quality control functions, as well as reduce flood peaks.

Purposes achieved by water projects and programs are outlined in Table 1.1. Human use of water is categorized in Table 1.1 by whether the water is withdrawn/diverted from its source or used in the stream without being withdrawn. Hydroelectric power generation, navigation, and recreation are major ways that people use water without removing it from stream/reservoir systems. Environmental management includes protecting or restoring water quality and maintaining stream flow quantities required for healthy ecosystems. Stormwater management and flood mitigation deal with problems of too much water.

TABLE 1.1 WATER RESOURCES DEVELOPMENT AND MANAGEMENT PURPOSES

- Water Supply Diversions with Consumptive Use
  -Municipal supply and use
  -Industrial supply and use
  -Agricultural supply and use
- Instream Water Use
  -Hydroelectric power generation
  -Inland navigation
  -Water-based recreation
- Environmental Management
  -Wastewater collection, treatment, and disposal
  -Water quality management
  -Protection/restoration/enhancement of biological resources
- Stormwater Management and Flood Mitigation
  -Stormwater drainage and management
  -Flood damage reduction
  -Erosion and sedimentation control
- Multiple-Purpose Development and Management

1.2.1 Municipal, Industrial, and Agricultural Water Supply

We use water in a myriad of ways. Water is diverted from rivers, lakes, and aquifers to supply municipal (domestic and public), rural domestic, livestock, agricultural irrigation, and various industrial uses. Consumptive use is water that is withdrawn and not directly returned to a stream or aquifer. Depending on the proportion of municipal water use devoted to lawn watering, flows returned to a river as wastewater treatment plant effluent may be about half the amount withdrawn. In terms of total withdrawals, the largest water use in the U.S. is cooling water for thermal-electric power plants. However, after circulating through the power plant cooling system, most of this water, now warmer, is returned to the river. Typical irrigation return flows range from none to almost half of the water withdrawn. Irrigation accounts for more consumptive use than any other water use sector.

Water use in the U.S. is summarized in Table 1.2 using data for the year 1995. The 554 billion cubic meters (m^3) of water withdrawn divided by the 1995 U.S. population of 267 million people results in a mean per capita water use of 2,070 m^3/year/person, which is equivalent to 5.68 m^3/day/person or 1,500 gallons/day/person. The consumptive use is 24.9 percent of the amount withdrawn; the other

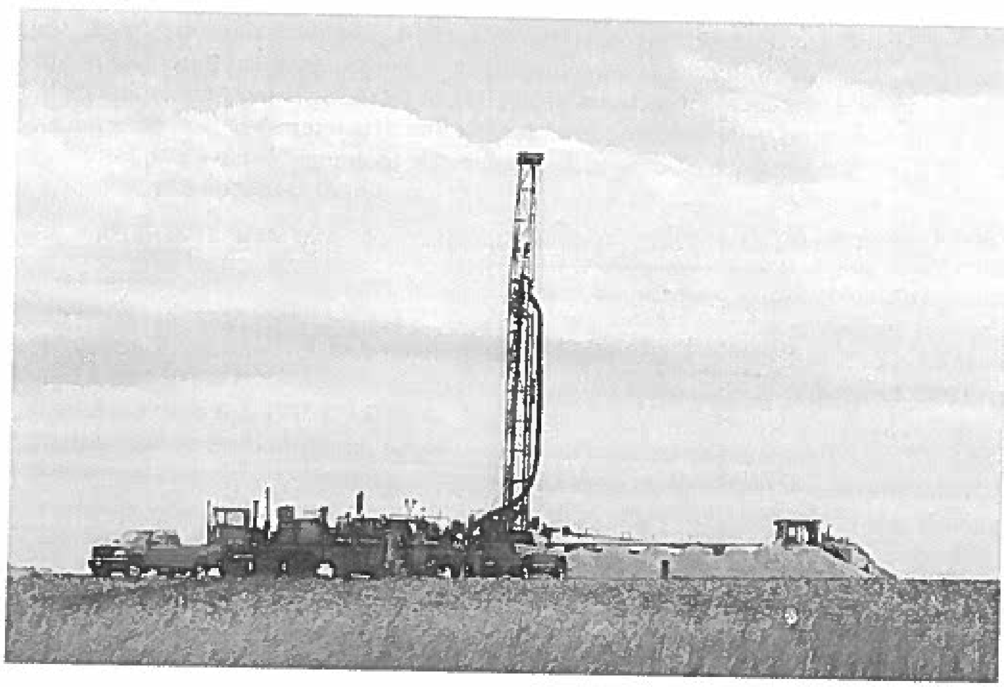

Figure 1.3 This 150 m (490 ft) well being drilled into the Ogallala Aquifer in Nebraska will supply a center pivot irrigation system. (Photo by R. A. Wurbs, June 2001)

TABLE 1.2 WATER USE IN THE UNITED STATES IN 1995 (GLEICK, 2000)

	Billion m^3/yr	Percent
1995 Withdrawals in the United States		
Agricultural irrigation	185	33.4
Rural domestic and livestock use	12	2.2
Municipal domestic and public use	56	10.1
Thermal-electric power plants	262	47.3
Other industrial uses	39	7.0
Total 1995 Withdrawals	554	100
Total 1995 Consumptive Use	138	24.9
Source of supply		
Surface water	447	80.7
Groundwater	107	19.3

75.1 percent is returned to its source. Surface water rivers and lakes and groundwater aquifers supply 80.7 and 19.3 percent, respectively, of the water withdrawn.

1.2.1.1 Irrigation Agricultural irrigation accounts for a third of total withdrawals in the U.S., 65 percent worldwide, and about 75 percent in developing countries (Chaturvedi, 2000). The 16 percent of cultivated land that is irrigated worldwide contributes 36 percent of total food production. The land areas being irrigated throughout the world in 1940, 1970, and 1995, respectively, comprised about 76, 242, and 256 million hectares. Fifty-four percent of the irrigated land is in four countries: China (20%), India (19%), the United States (8%), and Pakistan (7%). Irrigation increases crop yields and the amount of land that can be productively farmed, stabilizes productivity, facilitates a greater diversity of crops, increases farm income and employment, helps alleviate poverty, and contributes to regional development.

The earliest civilizations were developed in the Middle East and Asia along major rivers such as the Tigris, Euphrates, Nile, and Indus, which supplied water for irrigation. Increased demands for food accompanying population growth have resulted in irrigation projects worldwide over the past century. The Green Revolution of the 20th century relied heavily on water resources development and irrigation technology. Irrigation has been essential for the settlement and economic development of the dry western half of the United States. In recent years, in regions of the United States and elsewhere, use of water for irrigation has leveled off and even decreased due largely to depleting groundwater reserves and competition from cities for limited water resources.

1.2.1.2 Domestic water supply and sanitation worldwide. Basic domestic water supply and sanitation are fundamental to economic and social development and prevention of a multitude of diseases. The World Health Organization, the World Bank, and the U.S. Agency for International Development (USAID) estimates the minimum amount of water required for drinking, cooking,

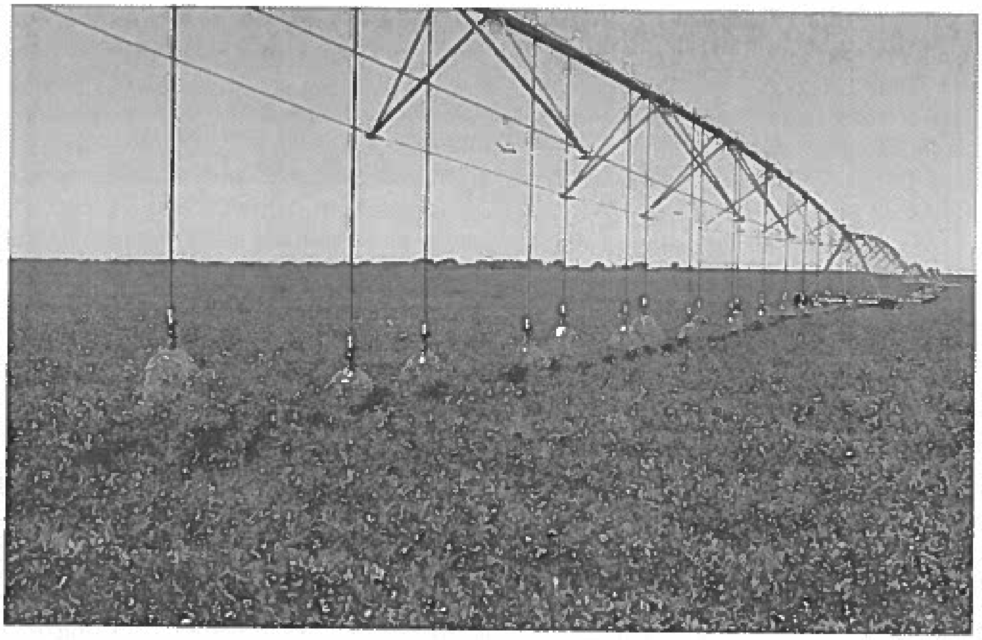

Figure 1.4 Low elevation spray application center pivot irrigation systems are used in the Winter Garden Region of South Texas shown here and elsewhere (New and Fipps, 2001).

cleaning, and sanitation range from 20 to 40 liters/day (5.3–10.6 gallons/day) per person. Per capita water use for household purposes, including lawn watering as well as indoor uses, varies greatly regionally throughout the United States, but about 300 liters/day (80 gallons/day) is a typical average per capita use rate. More than a billion people in the developing world lack safe drinking water that those in the developed nations take for granted. About half of the six billion people in the world live without access to adequate sanitation systems necessary for reducing exposure to water-related diseases. Construction of water supply and wastewater treatment facilities during the past century have dramatically reduced or eliminated typhoid fever, cholera, dysentery, and many other water-borne diseases in the developed nations. In the developing world, an estimated 14,000–30,000 people, mostly young children and the elderly, die every day from disease caused by drinking contaminated water or eating contaminated food (Gleick, 2000).

An airplane crash killing 300 people would be in the headlines of all major newspapers. The death toll attributable to inadequate water supply and sanitation is equivalent to such airplane crashes occurring every 15–30 minutes, 24 hours a day, 365 days a year. Those of us fortunate enough to live in nations with reliable, safe water supply systems, which we often take for granted, owe a great debt of gratitude to the engineering profession. Water resources engineers face a staggering challenge in responding to the needs of the developing world.

1.2.1.3 Water supply systems. Municipal, industrial, and agricultural water supply systems include sources of supply and facilities for storing, transporting, and distributing the water. Municipal and industrial systems also include treatment plants. Supply sources are usually river/reservoir systems and/or groundwater aquifers. Treatment of seawater, though very expensive, provides an alternative source for cities in coastal regions without access to rivers or aquifers. Farmers' crops are watered directly by precipitation and by irrigation. Wells are required to develop groundwater sources. Pipelines, pumps, and open channels serve to transport water between components of the supply system and distribute the water to consumers. Water distribution systems for large cities are typically comprised of thousands of pipelines and numerous pumps and storage facilities.

Dams, reservoirs, and appurtenant structures play a key role in water supply and multiple-purpose water management. Most of the rivers of the world are characterized by flows that are highly variable, random, and subject to extremes. In addition to cyclic seasonal fluctuations within each year, severe droughts with durations of several years and extreme flood events are major concerns. Reservoir storage is necessary to regulate stream flow fluctuations and develop reliable water supplies.

With increased hydrologic, environmental, and economic constraints on developing additional water supplies, demand management has become a major focus in the U.S. and elsewhere since the 1970's. Many cities waste much of their water through undetected pipeline leaks in aging water distribution systems. Agricultural irrigation delivery systems are notorious for losses due to seepage and evaporation. People use more water than they really need, with water inefficient landscaping and plumbing. Demand management measures may be categorized as long-term and short-term. Leak detection and repair, reuse of treated wastewater, pricing incentives, and water efficient plumbing, irrigation equipment, and landscaping achieve long-term reductions in water use. Rationing restrictions placed on water use during drought conditions is an emergency short-term measure.

1.2.2 Hydroelectric Power Generation

Electrical energy is produced by two types of plants, thermal and hydro. Most thermal plants use steam turbines and coal, natural gas, or nuclear fuel. As previously noted, circulation of water through the cooling systems of thermal-electric plants accounts for almost half of the water diverted from streams and aquifers in the U.S., although most of this water is returned to the streams. Hydroelectric generators are driven by water turbines. Many large electric power production systems include interconnected thermal and hydroelectric plants. Hydroelectric power generation is limited by water availability, but during wet periods, reliance on hydropower reduces fuel costs associated with the thermal plants. Thermal plants are often used to meet base-load requirements, supplemented by hydropower during times of peak energy demands.

Two-thirds of the 2,445,000 gigawatt-hours of electric energy generated by hydropower plants worldwide in 1996 were produced in the 10 countries listed in

TABLE 1.3 HYDROELECTRIC CAPACITY AND PRODUCTION IN 1996 (GLEICK, 2000)

Country	Installed capacity (megawatts)	Hydropower production (gigawatt-hours/year)	Percentage of country's total electrical energy
United States	74,860	296,380	10
Canada	64,770	330,690	62
China	52,180	166,800	18
Brazil	51,100	250,000	97
Russian Federation	39,990	162,800	27
Norway	26,000	112,680	99
France	23,100	65,500	15
Japan	21,170	91,300	9
India	20,580	72,280	25
Sweden	16,540	63,500	52
Total for 10 countries listed above	390,290	1,611,930	22
Worldwide total	633,730	2,445,390	20

Table 1.3. The 296,380 gigawatt-hours produced by hydroelectric plants in the U.S. represents about 10 percent of the total U.S. electric energy production. Hydroelectric plants account for about 20 percent of the total electric energy production worldwide. Hydropower supplies over 50 percent of the total electric energy supplied in each of 63 countries and over 90 percent of the electricity generated in 23 countries (Gleick, 2000).

Each hydroelectric power plant is unique with its own design. Hydropower projects normally include a dam, turbines, intake and conduit (called a penstock) to convey water to the turbines, generators, control mechanisms, housing for the equipment, transformers, and transmission lines. Trash racks, gates, forebay, surge tanks, and other appurtenant hydraulic structures may also be required. A tailrace, or channel, from the powerhouse back to the river is provided if the location of the turbines prevents discharge directly into the river. Hydropower plants may be classified as run-of-river, storage, or pumped storage. A storage-type plant has sufficient storage capacity to carry-over water from a wet season to a dry season or from year to year. Run-of-river plants have little storage and must use stream flow as it occurs. A pumped-storage plant generates energy during periods of peak demand, but during off-peak periods water is pumped from the tailwater pool back to the headwater pool.

1.2.3 Navigation

River navigation is another major instream use of water resources. Waterways have been important avenues of commerce in world history. Rivers offered comparatively easy routes through unmapped wilderness for the exploration of new lands. However, navigation on natural rivers is limited by sandbars, debris, and other obstructions, turbulent water, low flows, seasonal variations in flows, and floods. Consequently, extensive systems of channel improvements, canals, reservoirs, dams and locks, and bank stabilization measures have been constructed to facilitate navigation.

Petroleum, coal, construction materials, iron and steel products, grain, and other heavy bulky commodities are transported by barge on waterways relatively inexpensively compared with other alternative means of transport. However, river navigation has the disadvantage of being much slower than transport by rail or truck, and it is limited to serving cities located along the waterway. Other modes of transportation must be used to complete delivery of goods to locations away from the waterway system.

The navigation system of the United States consists of seven major groups of waterway routes with a total of 42,000 km of navigable channels that enable commercial water transportation to serve 38 states. This system includes the Atlantic Coast Waterways, Atlantic Intracoastal Waterway, Gulf Coast Waterways, Gulf Intracoastal Waterway, Mississippi River System, Pacific Coast Waterways, and Great Lakes System.

Navigation systems consist of natural and improved channels, man-made canals, contraction works, bank stabilization, and reservoir/dam/lock facilities. Where river flows are otherwise too shallow for navigation, dams are constructed to create sufficient depth. Lock structures allow boats and barges to pass through the dams. Canals are constructed to connect existing water bodies, to connect an inland city with a water body, and to circumvent unnavigable portions of a river such as rapids or falls.

Dredging consists of deepening and/or widening a channel by removing channel-bed material. Dredges are machines equipped with scooping or suction devices for removing debris and soil. Dredging is used to initially improve a channel where navigation is impeded by sandbars or deposits of silt. Annual maintenance dredging is commonly required to maintain adequate depths for navigation.

1.2.4 Environmental Management

Environmental management is concerned with minimizing the adverse effects of human activity on the environment. Environmental problems stem largely from population growth and the rising standard of living. The world population is over 6 billion and growing. Increased affluence in many nations, including the U.S. over the past century, has generated greater consumption of water, energy, and other resources and more pollution. Environmental management aspects of water resources engineering include wastewater collection, treatment, and disposal; protection and restoration of water quality in riverine and groundwater systems; and protection and enhancement of ecological systems and biological resources.

1.2.4.1 Wastewater collection, treatment, and disposal. Wastewater and sewage from homes, apartments, businesses, and industries are collected; pollutants are removed from the water; and the treated effluent is returned to a stream system. The elements of a municipal wastewater management system include: (1) individual sources of wastewater, (2) on-site processing facilities, (3) collection network, (4) conveyance to treatment plants, (5) treatment facilities, and (6) disposal facilities. Conventional municipal wastewater treatment plants use a multiple-step process: (1) removal of materials that will interfere with pumping and later treatment steps, (2) removal of the solid materials that will settle by gravity under quiescent conditions, (3) conversion of the remaining soluble and colloidal material into microbial solids, (4) removal of the remaining pollutant materials in a second sedimentation, and (5) treatment and disposal of the residual solids and sludges generated in the treatment process. Industrial facilities must either treat wastewater prior to discharge into a receiving water, or send it to a publicly owned municipal treatment plant, or in some cases, do both. Since industrial wastewater composition is highly variable, its treatment is very industry- and site-specific.

Wastewater treatment facilities in the United States are regulated by state environmental agencies in collaboration with the U.S. Environmental Protection Agency (EPA) through the National Pollutant Discharge Elimination System (NPDES). The Federal Water Pollution Control Act of 1948 provided a program for federal grants to municipalities for construction of wastewater treatment facilities, but funding was minimal relative to needs. In 1972, Congress amended the Water Pollution Control Act with Public Law 92-500 (PL 92-500), called the Clean Water Act, establishing programs that have greatly impacted water management, including the NPDES and federal grants for construction of publicly owned treatment works. Under the NPDES, the EPA requires each state to establish and enforce effluent limitations and performance standards for sources of water pollution, including wastewater treatment plants, industries, power plants, confined agricultural operations, and urban stormwater. PL 92-500 also established a massive construction grants program, providing several billion dollars of federal funds each year for the construction of municipal wastewater treatment plants that continued through the 1980's. The Water Quality Act of 1987 converted the construction grants to state-revolving loan programs, with state agencies administering loans to municipalities for construction of wastewater treatment plants and other water quality control projects.

1.2.4.2 Water quality management. Water quality management is concerned with the control of pollution from human activity so that the water is not degraded to the point that it is no longer suitable for intended uses. The uses of streams, rivers, lakes, and groundwater are greatly influenced by water quality. Activities such as hydropower generation, navigation, fishing, swimming, and potable water supply have different requirements for water quality. Particularly high quality is required for potable water supplies. In many parts of the world, municipal and industrial wastewater discharges and other human activities have transformed pristine natural streams with abundant fish and diverse ecological systems into foul open sewers with few life forms and fewer beneficial uses.

Domestic sewage and industrial wastes are called point sources because they are generally collected by a system of pipes or channels and conveyed to definite points of discharge into receiving water. Urban and agricultural runoff characterized by multiple disperse discharge sites are called nonpoint sources. Major categories of pollutants include oxygen-demanding material, typically biodegradable organic matter; nutrients, primarily nitrogen and phosphorous; pathogenic organisms; suspended solids; salts; toxic metals and toxic organic compounds; and heat.

Surface water quality in the United States has improved more since the 1970's than perhaps any other area of the environment. The Clean Water Act of 1972 (PL 92-500) established national water quality goals and created programs to implement the goals, including the previously noted NPDES permit system and federal funding of municipal wastewater treatment facilities. Water quality in the U.S. was dreadful prior to the 1970's. Cities and industries dumped large quantities of poorly treated or raw wastewater directly into many of our rivers and lakes. Today most, although not all, surface waters are in much better condition. Although much has been accomplished, more work is required. Some municipalities and industries have still not met the standards. Nonpoint pollution, such as agricultural fertilizers and pesticides and urban stormwater runoff, account for much of the present pollution.

Groundwater is a major source of domestic and public water supply. Treatment usually consists of chlorination and perhaps removal of iron and manganese or other specific constituents. Groundwater is typically viewed as being protected from pollution by overlying formations. However, since the 1970's, many aquifers in the U.S. have been found to be contaminated by compounds other than those present in the natural environment. Many of the compounds that have been found in groundwater are known to be carcinogenic and/or mutagenic. Sources of groundwater contamination include leachates from municipal and industrial solid waste landfills; land disposal of sludges from municipal and industrial wastewater treatment plants; industrial waste storage ponds and lagoons; septic tanks; underground storage tanks; hazardous waste disposal sites; deep-well injection of wastes; deicing of roads; accidental spills; agricultural pesticides, herbicides, and fertilizers; animal feedlots; mining; and saltwater intrusion. Groundwater aquifers are somewhat protected from surface contamination by overlying earth formations. However, being located at a depth into the earth also makes clean up of contaminated aquifers extremely difficult.

1.2.4.3 Protection and restoration of biological resources. Environmental management is concerned with water quantity as well as water quality. Agricultural, industrial, and municipal water supply diversions often conflict with environmental instream flow needs. Instream flow requirements include suitable stream flow amounts and seasonal variations to support fish, wildlife, and diverse ecological systems. Freshwater inflows into bays and estuaries are required to maintain proper salinity gradients for estuarine ecosystems. Environmental instream flow requirements are important considerations in water rights permitting programs and reservoir system operations.

Protection and restoration of wetlands is another important issue in water management. Wetlands occur in many forms, including swamps, bogs, marshes, shallow lakes, sloughs, flood plains, and estuaries. Water inundates or is near the surface of the ground for much of the year. Wetland ecosystems represent the transition between terrestrial and aquatic systems. Wetlands play important roles in the natural environment, including supporting ecosystems, naturally removing pollutants from water, and mitigating flooding. About half of the original wetlands in the U.S. have been lost through agricultural and urban development. In the 1980's, the federal government adopted policies and programs to prevent further loss of wetlands. In addition to natural wetlands, there are a growing number of restored, created or artificial, and constructed wetlands. Restored wetlands are those that existed as wetlands previously, but have had to be restored to their original conditions after being converted to dry land. Created or artificial wetlands are those that are built in previously dry areas to emulate natural wetlands. They are often created to mitigate the loss of wetlands at other locations due to construction or land development activities. Constructed wetlands may also be created specifically to serve as water treatment systems using wetland processes.

1.2.5 Stormwater Management, Flood Mitigation, and Erosion Control

Stormwater management, drainage, flood mitigation, and mitigation of erosion and sedimentation deal with problems caused by precipitation and runoff, particularly during periods of excessively high rainfall and/or snowmelt. Stormwater drainage refers to the runoff of precipitation from a watershed to a major stream. Flood mitigation addresses problems associated with the overflow of major streams. Although also occurring during nonflooding periods, erosion and sedimentation problems are generally associated with significant storms.

1.2.5.1 Stormwater management. Stormwater management is a major consideration for essentially all municipalities, small and large. Urban drainage systems include streets, curbs and gutters, ditches, channels, streams, culverts and bridges, and storm sewer networks, including pipes, inlets, and other appurtenant structures. The purpose of such systems is to collect and convey rainfall to a stream system. Drainage improvements are necessary to prevent ponding of water in streets, homes, and properties. However, efficient drainage also results in higher peak flows occurring downstream. Stormwater management entails a more comprehensive consideration of detention storage and other strategies for detaining runoff, as well as drainage improvements for expediting runoff.

Urbanization often results in significant increases in storm runoff as buildings, parking lots, and streets replace pastures and woods. Stormwater management strategies are often based on mitigating the increases in runoff to protect downstream properties. Detention basins of various configurations represent the most common approach for limiting postdevelopment peak flows to predevelopment conditions.

Precipitation runoff from urban areas washes off soil, lawn fertilizers, oil from streets, debris, and other contaminants and transports them to streams. The Water Quality Act of 1987 mandated incorporation of urban stormwater in the NPDES permit process. Stormwater permits became a major consideration for cities during the 1990's.

Drainage is also a major consideration for transportation engineers. Streets, highways, and railroads cross rivers, streams, and drainage channels. Bridges and culverts are constructed for these crossings. Provisions are also required to drain rainfall from pavements and adjacent right-of-ways. Drainage is an important component of airport design. Stormwater management is also important in agriculture, mining, and other industrial sectors.

1.2.5.2 Flood mitigation. Floodplain lands near rivers and other water bodies offer significant advantages for locating cities and agricultural development. Proximity to rivers facilitates water supply and wastewater disposal, recreation, and provision of other water-related services. The aesthetics of tree-lined streams attract residential development. Floodplain fertility encourages agriculture. However, human activities result in susceptibility to damage as rivers naturally overflow their banks periodically. Floodplains are a natural part of a stream system. Coastal areas are subject to flooding associated with tropical storms and hurricanes.

River and coastal flooding are major problems throughout the world. The Flood Control Act of 1936 and subsequent legislation initiated major federal programs for constructing flood control projects throughout the United States. The U.S.

Figure 1.5 The April 2001 flood on the Mississippi River inundated these homes in Campbell's Island, Illinois. (Courtesy of Federal Emergency Management Agency.)

Figure 1.6 Rescue workers patrol flooded streets in Davenport, Iowa, in April 2001. (Courtesy of Federal Emergency Management Agency.)

Army Corps of Engineers (USACE) constructed numerous dams, levees, floodwalls, and channel improvements on the major rivers of the nation during the 1930's–1970's. The Natural Resource Conservation Service (NRCS) has constructed many thousands of flood-retarding structures controlling flood flows from smaller watersheds. Nonfederal entities also construct and maintain flood control facilities.

These flood control structures, with few exceptions, have functioned as designed and greatly reduced flood damages. However, as illustrated by Figs. 1.7 and 1.8, flood losses have continued to increase nationwide, despite the large investments in flood control structures, as a result of intensified development of floodplain lands. People tend to build their homes and businesses near streams. Essentially all cities and towns are superimposed on a system of natural and man-altered streams.

The National Flood Insurance Program (NFIP) was established pursuant to the National Flood Insurance Act of 1968 as amended by the Federal Flood Disaster Protection Act of 1973 to supplement structural measures with nonstructural approaches. About 20,000 communities participate in the NFIP. Flood insurance is available to the citizens of participating communities. Participating local communities are required to enact and enforce floodplain management regulations. Hydrologic and hydraulic studies are performed to delineate floodplains. The

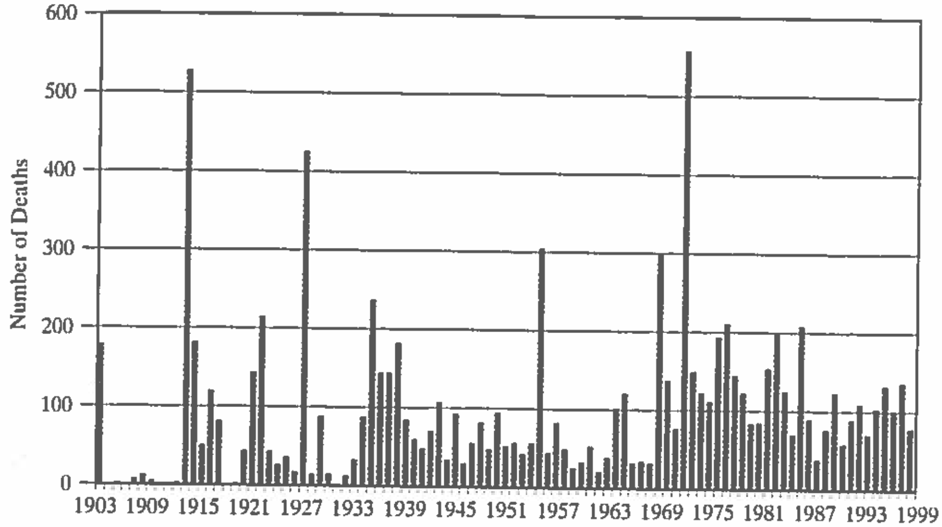

Figure 1.7 Flood-related deaths in the United States each year from 1903 to 1999. (National Weather Service.)

floodplain delineations continue to be updated to reflect watershed land use changes, floodplain encroachments, and construction of stormwater management and flood control improvements. Building of homes and businesses within the 1.0 percent annual exceedance frequency floodplain is either prohibited or must

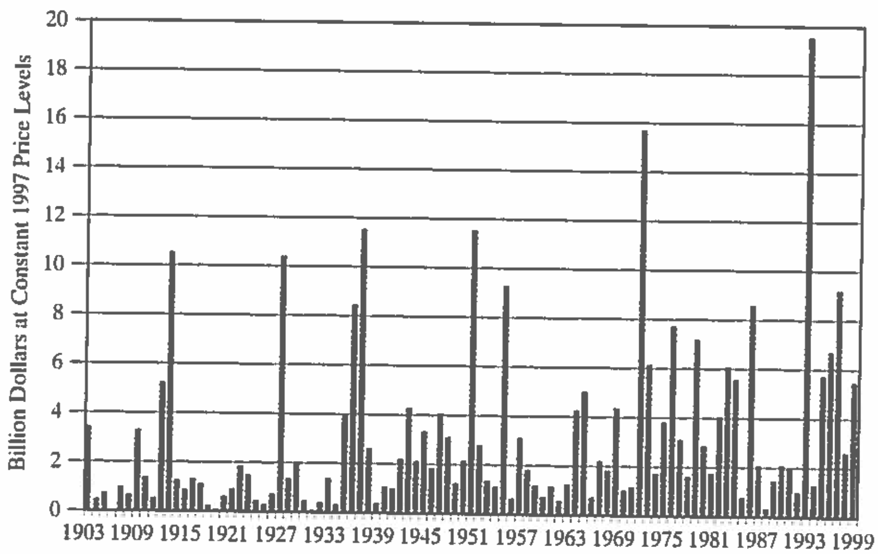

Figure 1.8 Flood damages in the United States in constant 1997 dollars. (National Weather Service.)

meet specified requirements. The objective is to manage floodplain land use and reduce susceptibility to damage. Thus, flood mitigation or flood damage reduction strategies include integration of both nonstructural measures and flood control structures.

1.2.5.3 Erosion and sedimentation mitigation. Erosion and transport of soil particles, called sediments, by rainfall and flowing water are key processes in shaping the landscape of a river basin and have important economic and environmental consequences. Land erosion is greatly accelerated by farming activities and construction projects. Land erosion may destroy farmland and seriously impact urban areas. Streams meander or alter their courses through streambank erosion and sediment transport and disposal processes. Human development adjacent to streams may be adversely affected by streambank erosion. Sediment fills reservoirs, highway culverts, navigation channels, and wetlands. Other contaminants transported with sediments, as well as the sediments themselves, affect water quality.

Agricultural soil conservation practices include contouring, strip cropping, and terracing. Streambank erosion control measures include revetments and lining materials, such as vegetation, rock riprap, and concrete. A variety of measures are applied in construction activities, such as highway projects, to prevent bare soil from being washed off the construction site.

Hydraulic structures often drastically increase flow velocities and require stilling basins and other energy dissipation measures. Erosion control below dam outlet structures and highway culverts, around bridge piers, and in association with other types of hydraulic structures is a common problem addressed by water resources engineers.

1.3 THE WATER MANAGEMENT COMMUNITY

The water management community includes local, regional, state, national, and international governmental entities, private water suppliers, engineering firms, construction companies, equipment suppliers, various industries that use water, environmental and other interest groups, and individual water users, which includes all of us. Water management is highly political, as well as technical. Water is a public resource owned by the state and used by the people. Water supply needs and practices vary greatly between nations, particularly between developed and third world countries. The prosperity and survival of people worldwide in the 21st century depend on the ability of complex water management communities in the nations of the world to deal with the uneven geographic and temporal distribution of water resources and to protect the water from pollution.

Water resources engineers in the United States work within the organizational setting outlined in Table 1.4. The entities listed in the table are interconnected, working together and interacting in a variety of ways. Thus, an engineer employed

TABLE 1.4 THE WATER MANAGEMENT COMMUNITY IN THE UNITED STATES

Private Sector

Engineering consulting firms
Construction contractors, Equipment suppliers
Private water suppliers
Industrial water users, Farmers, Developers

Local Public Agencies	*Interstate Regional Agencies*
Cities	River basin commissions
Water districts	Tennessee Valley Authority http://www.tva.com

State Agencies

California Department of Water Resources http://www.dwr.water.ca.gov
California Water Resources Control Board http://www.swrcb.ca.gov
Texas Water Development Board http://www.twdb.state.tx.us
Texas Natural Resource Conservation Commission http://www.tnrcc.state.tx.us
Florida Department of Environmental Protection http://www.dep.state.fl.us/org/
Illinois State Water Survey http://www.sws.uiuc.edu
Numerous other water agencies in the 50 states

Federal Agencies

Army Corps of Engineers (USACE) http://www.usace.army.mil
Bureau of Reclamation (USBR) http://www.usbr.gov
Natural Resource Conservation Service (NRCS) http://www.nrcs.usda.gov
Geological Survey (USGS) http://www.usgs.gov
National Weather Service (NWS) http://www.nws.noaa.gov
Federal Emergency Management Agency (FEMA) http://www.fema.gov
Federal Energy Regulatory Commission (FERC) http://www.ferc.fed.us
Fish and Wildlife Service (USFWS) http://www.fws.gov
Environmental Protection Agency (EPA) http://www.epa.gov

International Agencies

United Nations System agencies and programs http://www.un.org
U.S. Agency for International Development http://www.usaid.gov
International Boundary and Water Commission http://www.ibwc.state.gov

Professional Societies and Associations

Environmental and Water Resources Institute (EWRI) http://www.ewrinstitute.org
of the American Society of Civil Engineers (ASCE) http://www.asce.org
American Water Resources Association (AWRA) http://www.awra.org
International Water Resources Association (IWRA) http://www.iwra.siu.edu
American Water Works Association (AWWA) http://www.awwa.org
Water Environment Federation (WEF) http://www.wef.org
American Institute of Hydrology (AIH) http://www.aihydro.org
National Groundwater Association (NGWA) http://www.ngwa.org
Association of State Floodplain Managers (ASFPM) http://www.floods.org
Universities Council on Water Resources (UCOWR)
http://www.uwin.siu.edu/ucowr/

Universities

by any one of them should also have a general understanding of the activities of the others.

The water agencies maintain web sites, with addresses shown in Table 1.4, that describe their missions and programs and provide access to a wealth of information, including announcements of current activities and employment opportunities, directories of people to contact for various types of assistance, technical publications, computer software, and databases. The addresses shown provide connections to numerous other sites. For example, the centralized federal agency web sites provide connections to sites for their regional and field offices and research organizations.

Table 1.4 highlights key entities with water management responsibilities, but certainly is not a comprehensive listing of all organizations with interests in water resources engineering. For example, hydrologic and hydraulic design of bridges and drainage facilities is a major concern for engineers in state transportation departments that are not included in the table. Many agencies responsible for managing public lands and other related resources are not listed. The water-related work of the organizations listed in Table 1.4 is performed by water resources engineers and other water professionals. Many volunteer groups, not listed, also play important roles in the water management community. Environmental and natural resource conservation organizations encourage wise stewardship of water resources. Other organizations have been created to lobby for political support for various types of water development projects. A myriad of local and regional citizen advisory groups guide water management in their local areas.

1.3.1 Private Industry

Engineering consulting firms perform feasibility and design studies, construction supervision, and other professional services for the other water management entities listed in Table 1.4. A majority of the thousands of civil engineering consulting firms in the U.S. include water resources engineering in their repertoire of expertise. Many specialize exclusively in water resources engineering. Consulting firms range in size from one professional engineer working alone to firms with several thousand employees in many offices located throughout the nation and world. The public agencies listed in Table 1.4 accomplish their water resources engineering work with various combinations of in-house expertise and contracts with consulting firms.

Construction contractors are hired by many of the entities listed in Table 1.4 to construct water projects. Equipment suppliers manufacture and sell pumps, pipes, irrigation equipment, and the various other types of equipment required for water management systems.

Of the myriad industrial water users, electric power utilities divert the most water. Farmers irrigating their crops account for the largest consumptive use of water. Water supply, sewage collection, drainage, and stormwater management are major concerns to developers who build residential neighborhoods, commercial facilities, and other land development projects.

1.3.2 Local Public Agencies

Cities provide water supply and wastewater management services to their citizens and industrial customers. Drainage, stormwater management, and flood mitigation are also important functions of municipal government. The professional staff of public works, development services, planning, and engineering departments of cities perform some of their water resources engineering work in-house and contract with consulting firms to perform other work.

Municipal water districts are created to develop and operate regional water supply and wastewater management facilities for multiple member cities. The regional approach is often more efficient than each city owning and operating its own individual facilities. Likewise, urban drainage and flood control districts encompass geographic areas larger than a single city. Agricultural levee districts allow farmers to pool their resources to protect their land from flooding. Soil conservation districts work to mitigate agricultural land erosion and manage land and water resources. Groundwater conservation districts are created to manage the use of particular aquifers. River authorities have comprehensive river basin management responsibilities.

1.3.3 Interstate Regional Agencies

Water agencies in the U.S. are created primarily at the local, state, and federal levels. Various interstate river basin commissions, compact commissions, and other governmental bodies have been established to allocate the water resources of interstate river basins between the affected states and to coordinate water management. However, the Tennessee Valley Authority (TVA) is unique in its comprehensive role in developing and managing the water resources of a multiple-state region.

The TVA was created by the federal government in 1933 as a regional agency to promote economic development and social betterment of a depressed area of the nation. In 1933, land in the Tennessee River Valley was underdeveloped and neglected; heavy rainfall had eroded the soil; and the forests had been cut over and burned. Almost every community along the major streams was subject to flood damage. Heavy flows from the Tennessee River also contributed to flooding on the Ohio and Mississippi Rivers. The TVA was charged with planning for the proper use, conservation, and development of the natural resources of the Tennessee River Basin. This was to be accomplished through flood control, power production, navigation, reduction of soil erosion, afforestation, elimination of agricultural use of marginal lands, industrial development and diversification, and community development.

The Tennessee River Basin encompasses portions of Alabama, Georgia, Kentucky, Mississippi, North Carolina, Tennessee, and Virginia. The Tennessee River flows into the Ohio River just above its confluence with the Mississippi River. The TVA is the largest public power company in the U.S., with 28,500 megawatts of

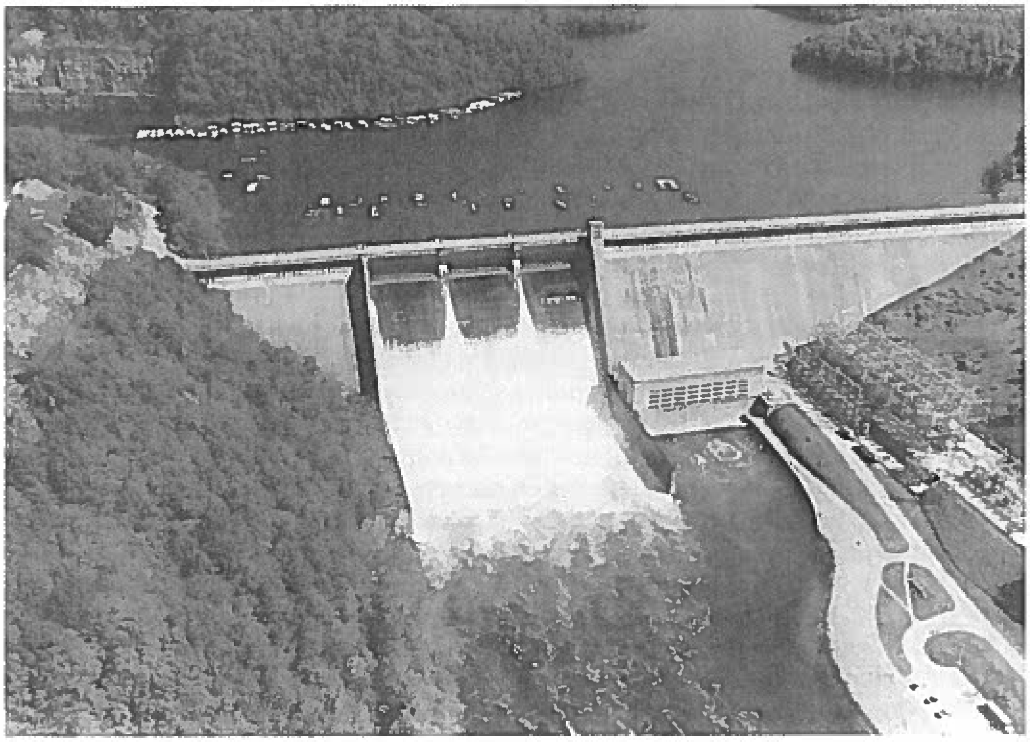

Figure 1.9 Norris Dam on the Clinch River in Tennessee was the first dam constructed by the TVA and is operated by the TVA for flood control, hydropower, water supply, and recreation. (Courtesy of Tennessee Valley Authority.)

dependable generating capacity. TVA's power facilities include 11 fossil-fuel plants, 3 nuclear plants, 29 hydroelectric plants, and 27,000 km of transmission lines. The TVA operates a multipurpose reservoir system with 50 dams and appurtenant structures for flood control, hydroelectric power, water supply, navigation, fish and wildlife, and recreation. The 10 dams on the main stem of the Tennessee River have navigation locks facilitating barge traffic on the 1,000-km reach from the Ohio River to the city of Knoxville, Tennessee.

1.3.4 State Agencies

State water agencies are different in the different states, having evolved historically in response to varying needs and conditions. Several of the larger state agencies are noted here to illustrate the types of state organizations functioning across the U.S.

The California Department of Water Resources was created by the California Legislature in 1956 to plan and guide the development of the state's water resources. The agency now has a staff of 2,700 people. Responsibilities include preparing and updating the state water plan, providing technical and financial assistance to local communities, administering a dam safety program, collecting and distributing data, and operating the State Water Project—one of the largest water development and distribution systems in the nation. The State Water Resources Control Board, created by the California Legislature in 1967, administers regulatory programs to protect water quality and allocate water resources. Nine regional Water Quality Control Boards develop and implement plans for protecting water quality.

The Texas Natural Resource Conservation Commission, with 3,000 employees, is another of the larger and more comprehensive state environmental regulatory agencies in the nation. The agency administers an assortment of regulatory programs, including water quality and water rights permit programs. The Texas Water Development Board prepares and updates the state water plan, administers a variety of grant and loan programs, and maintains a centralized data bank called the Texas Natural Resources Information System. Nineteen river authorities in Texas serve as nonfederal sponsors for federal projects; construct and operate multipurpose reservoir projects, regional water supply systems, and hydropower plants; and perform other basinwide planning and management responsibilities.

Florida is divided into five regions, with a water management district responsible for multipurpose water management for each region, including planning, project development, financing, and regulatory functions. The five water management districts have a total of about 3,200 employees. The Florida Department of Environmental Protection, with 3,000 employees, exercises general supervisory authority over the water management districts, administers programs statewide to protect air and water quality, ensures proper waste management, and manages state parks and other lands.

The Illinois State Water Survey is a division of the Office of Scientific Research and Analysis of the Illinois Department of Natural Resources and is affiliated with the University of Illinois. The State Water Survey conducts investigations, performs applied research, and disseminates information regarding groundwater and surface water resources and atmospheric science.

1.3.5 Federal Agencies

Each of the federal agencies listed in Table 1.4 has multiple missions. The three agencies that construct and operate water resources development projects, along with other water management responsibilities, are the USACE, U.S. Bureau of Reclamation (USBR), and the Natural Resource Conservation Service (NRCS). The responsibilities of the U.S. Geological Survey (USGS) and the National Weather Service (NWS) deal primarily with collecting and managing data and disseminating information used throughout the water management community. The Federal Emergency Management Agency (FEMA) administers the NFIP and emergency relief programs for responding to the full spectrum of disasters, including floods, droughts, and hurricanes. The EPA and the Federal Energy Regulatory Commission (FERC) are regulatory agencies.

The USACE is the nation's oldest and largest water resources development and management agency. The Corps traces its military roots to the founding of the nation, with its water development program beginning with the construction of navigation improvements in the 1800's. The agency employs 34,600 civilian and 650 military men and women. The Corps is organized geographically into 8 divisions that are further subdivided by river basins into 40 districts in the U.S. Other offices are located throughout Europe and Asia primarily to support military functions. USACE water research and development organizations include the Engineering Research and Development Center (formerly called the Waterways Experiment Station) in Vicksburg, Mississippi; Hydrologic Engineering Center in Davis, California; and Institute for Water Resources in Alexandria, Virginia. In addition to its extensive water resources development and management activities, the USACE is responsible for designing and managing construction of military facilities for the Army and Air Force and providing similar support for other federal agencies. Water resources engineering expertise is important in accomplishing military construction as well as water management responsibilities.

The USACE civil works program includes planning, design, construction, and operation of water resources development projects, as well as other water resources planning, research, and regulatory activities. The Corps has constructed and now maintains and operates most of the inland navigation facilities in the U.S. and over 500 major multipurpose reservoir projects nationwide. The agency has constructed numerous flood control levee and channel improvement projects that have been turned over to local project sponsors for maintenance. Under authority of Section 404 of the Clean Water Act of 1977, the USACE administers a permit program regulating construction and other activities involving dredging and/or filling in rivers, streams, and wetlands. The Section 404 permit process ensures that all construction projects and other filling or dredging activities are in compliance with all federal environmental protection laws and requirements. Obtaining a Section 404 permit from the USACE is an important aspect of private and public development projects.

The USBR of the Department of the Interior was created by the Reclamation Act of 1902 to plan and implement water projects needed to support population and economic growth in the arid West. The USBR is responsible for development and management of water resources in the 17 western states for multiple purposes, including irrigation, hydroelectric power, municipal and industrial water supply, pollution abatement, propagation of fish and wildlife, recreation, erosion control, and flood control. The Bureau has constructed more than 230 dams, including some of the largest in the nation. Bureau projects supply wholesale municipal water to 31 million people and irrigation water to 140,000 farmers for irrigating 4 million hectares of farmland in the dry West that produce 60 percent of the nation's vegetables and 25 percent of its fruits and nuts. USBR's 58 hydroelectric power plants produce 40 billion kilowatts of electricity per year to serve 6 million homes.

The NRCS (formerly called the Soil Conservation Service) of the Department of Agriculture, dates back to the 1930's. The NRCS conducts national programs

Figure 1.10 The USBR operates Hoover Dam to regulate the flow of the Colorado River to supply water for Las Vegas, Los Angeles, other cities, agricultural irrigators, and environmental instream flow needs; meet flow commitments to Mexico; generate hydroelectric power; and control floods. (Photo by W. P. James, June 1998)

dealing with soil and water conservation and small watershed flood protection. The NRCS works closely with farmers, ranchers, landowners, environmental groups, and state and local organizations in carrying out its programs. The NRCS is linked with 3,000 conservation districts, essentially one in every county nationwide, organized by local citizens under state law. The NRCS has 10,800 full-time and 1,650 part-time and temporary employees. Partners include 17,000 unpaid conservation district officials, 8,000 permanent conservation district employees, and many thousands of volunteers associated with environmental conservation groups. The NRCS has constructed many thousands of relatively small flood control dams and other structures on private and public lands and provides technical water resources engineering assistance for its local collaborators.

The mission of the Water Resources Division (WRD) of the USGS, of the Department of the Interior, is to provide the hydrologic information and understanding needed to support management and use of the nation's water resources. The USGS organizational structure includes 48 district offices generally located in state capitals and four regional offices. The USGS WRD conducts three major types of interrelated activities: (1) data collection and dissemination, (2) problem-oriented water resources appraisals and interpretive studies, and (3) research. Data collection programs provide water quality and quantity data for stream flow, reservoir storage, and groundwater. Data are stored in computer-based data management systems accessible to the public, as well as printed in published reports. The water management community relies heavily on USGS water data.

Other divisions of the USGS provide mapping products and services and information regarding geological and biological resources. Topographic quadrangle maps with nationwide coverage and related mapping products developed by the USGS are used extensively by water resources engineers. Maps are in both paper and digital formats.

The NWS is responsible for the hydrologic services programs of the National Oceanic and Atmospheric Administration of the Department of Commerce. The NWS provides weather, hydrologic, and climate forecasts and warnings for the U.S., its territories, and adjacent waters and ocean areas. The NWS also collects and disseminates weather and climatic data, which is widely used throughout the water management community.

The mission of FEMA, created in 1979, is to reduce loss of life and property and protect the nation's infrastructure from all types of hazards through a comprehensive, risk-based, emergency management program of mitigation, preparedness, response, and recovery. FEMA has 2,500 employees supplemented by over 5,000 stand-by disaster reservists from other agencies. The Flood Insurance Administration of FEMA administers the flood insurance component of the previously noted NFIP, and the Mitigation Directorate of FEMA oversees the floodplain management aspect of the program.

FERC is the agency within the Department of Energy that regulates the transmission and sale of natural gas, oil, and electricity in interstate commerce and licenses and inspects private, municipal, and state hydroelectric projects.

Hydroelectric power regulation includes issuing preliminary permits, project licenses, and exemptions from licensing; ensuring dam safety; performing project compliance activities; and coordinating with other agencies.

The U.S. Fish and Wildlife Service (USFWS) is responsible for enforcing wildlife laws, protecting endangered species, and conserving and protecting wildlife and wildlife habitat on public and private lands nationwide. These responsibilities significantly affect the activities of other agencies in developing and managing water projects. The USFWS also manages a system of 520 national wildlife refuges and thousands of wetlands and other special management areas and operates 66 national fish hatcheries, 64 fishery resources offices, and 78 ecological services offices. The USFWS employs 7,500 people in facilities across the nation.

The EPA was established in 1970 to consolidate in one agency a variety of federal research, monitoring, standard-setting, and enforcement activities to ensure environmental protection. EPA's mission is to protect human health and to safeguard the natural environment (air, water, and land) on which life depends. The EPA has grown from 4,084 employees in 1970 to more than 18,000 since 1998. EPA headquarters is in Washington, D.C. Regional offices in each of 10 regions of the U.S. are responsible for execution of EPA's programs within the states in that region. The EPA Office of Research and Development operates 14 national laboratories. The EPA Office of Water, working through the EPA regional offices in collaboration with state environmental agencies, is responsible for implementing the Clean Water Act, Safe Drinking Water Act, and other federal laws pertaining to protection of water quality, public health, and environmental resources. The NPDES, safe drinking water programs, and an array of other regulatory activities are accomplished largely through issuance and enforcement of permits by state regulatory agencies that meet requirements outlined by the federal EPA.

1.3.6 International Agencies

The United Nations (UN) System, consisting of the UN itself and over 30 affiliated organizations, is central to global efforts to solve a broad diversity of problems that challenge humanity. The UN was established in 1945 with the mission of preserving peace through international cooperation and collective security. The 189 member countries account for most of the nations in the world. The United States (25%), Japan (18%), Germany (9.6%), Italy (5.4%), the United Kingdom (5.1%), and Russia (2.9%) contribute over 72 percent of the regular UN budget. About 52,100 people work in the UN System.

The International Monetary Fund, the World Bank group, and 12 other independent organizations known as *specialized agencies* are linked to the UN through cooperative agreements. These agencies are autonomous bodies created by intergovernmental agreement. In addition, a number of other UN programs, funds, and offices report to the UN General Assembly or the Economic and Social Council. These organizations have their own governing bodies, budgets, and secretariats. These agencies and programs along with the UN are collectively known as the UN

System or UN family. They provide coordinated yet diverse programs to improve the economic and social conditions of people around the world.

The UN System organizations for which water is a key concern include the World Bank, the World Health Organization, the World Meteorological Organization, the International Fund for Agricultural Development, and the UN Development Program (UNDP). For example, the World Bank provides funds and technical assistance to developing countries to reduce poverty and advance sustainable economic growth. Likewise, the UNDP supports technical support of development projects for developing nations. Many of the World Bank and UNDP projects involve multipurpose water resources development projects and/or water supply and sanitation services.

In addition to participating in the UN System, the United States also has its own programs for helping people in other countries. USAID is the principal U.S. agency responsible for extending assistance to countries recovering from disaster or trying to escape poverty. Water is a key concern. USAID has headquarters in Washington, D.C., and field offices throughout the world.

Worldwide, two or more countries share each of 261 international river basins. Water allocation, cooperation, and conflict mitigation are important aspects of water management in these shared river basins. For example, the United States and Mexico share the waters of the Rio Grande and Colorado River Basins. The International Boundary and Water Commission (IBWC) consists of a Mexican Section and a U.S. Section, with headquarters in the adjoining cities of El Paso, Texas, and Ciudad Juarez, Chihuahua.

The international boundary between the U.S. and Mexico follows the middle of the Rio Grande from its mouth on the Gulf of Mexico 2,019 km to a point just upstream of El Paso, Texas. From there, the boundary follows an alignment westward overland for 858 km to the Colorado River, follows the middle of that river for 38 km, and then extends overland for 226 km to the Pacific Ocean. By the Convention of 1889, the governments of the two countries established the International Boundary Commission to settle questions regarding the location of the boundary when the rivers changed their course. A 1944 treaty allocating the waters of the Rio Grande and Colorado River between the two nations also changed the name of the International Boundary Commission (IBC) to the IBWC. The IBWC administers the allocation of the waters of the two river basins between the two nations and operates a multipurpose reservoir system on the Rio Grande for water supply, flood control, hydroelectric power, and recreation. The IBWC also conducts planning studies and implements projects for border water supply and sanitation, salinity mitigation, local flood control, and stream bank stabilization.

1.3.7 Professional Societies and Associations

Several of the many water-related professional societies and associations are listed in Table 1.4. These organizations facilitate sharing of information, foster professional growth of its members, influence political processes, and provide leadership in continually improving the effectiveness of the professional community in serving the public. The professional societies are perhaps best known for their journals and other publications and technical conferences and meetings.

The 123,000 member American Society of Civil Engineers (ASCE) founded in 1852 is the oldest engineering society in the nation. Technical specialty area activities within ASCE, as reorganized in the late 1990's, are focused in the following institutes: Geo-Institute; Structural Engineering Institute; Architectural Engineering Institute; Construction and Materials Institute; Coasts, Oceans, Ports, and Rivers Institute; and Environmental and Water Resources Institute (EWRI). The ASCE EWRI has 20,000 members and over 100 active task committees working on manuals of practice and technical standards, as well as providing commentary on public policy issues. The EWRI holds several annual technical conferences and publishes the following journals.

- *Journal of Environmental Engineering*
- *Journal of Hydraulic Engineering*
- *Journal of Hydrologic Engineering*
- *Journal of Irrigation and Drainage Engineering*
- *Journal of Water Resources Planning and Management*

1.3.8 Universities

The important roles of universities in the water management community include educating undergraduate and graduate students, providing continuing education opportunities for practicing engineers, research, publications, and service activities. Water resources engineering is a subject or option program in undergraduate civil, environmental, and agricultural engineering curricula and a major specialty area for graduate study. Basic and applied research contributes to the knowledge base of the array of engineering and scientific fields related to water. Many universities have water resources institutes or centers to support interdisciplinary research in water resources.

1.4 COMPUTER MODELS IN WATER RESOURCES ENGINEERING

The term *model* may be defined as any simplified representation of a real-world system. The discussion here deals with representing water-related systems with mathematical formulations that are solved using a computer. Computer modeling of natural and man-made water resources systems is a central focus in water resources engineering. Most of the analysis techniques presented in this textbook are implemented, in professional practice, using computers.

TABLE 1.5 CATEGORIES OF COMPUTER SOFTWARE

General-Purpose Commercial Software	
Spreadsheet-based packages	Excel by Microsoft Corporation Lotus 1-2-3 by Lotus Development Corporation Quattro Pro by Borland International, Inc.
Mathematical modeling environments	MATLAB by The MatWorks, Inc. MathCAD by MathSoft, Inc. Mathematica by Wolfram Research, Inc.
Geographical information systems	ArcInfo, ArcView, and ArcGIS by ESRI
Computer-aided drafting and design	AutoCAD by Autodesk, Inc. MicroStation by Intergraph Corporation
High-Level Programming Languages	
Fortran	Compaq Computer Corporation, Lahey Computer Systems, Inc., and other companies
C, C++, BASIC	Microsoft Corporation and other companies
Generalized Water Resources Engineering Models	
See Table 1.6	

Different types of software tools available for building models are outlined in Table 1.5. Categories of software include (1) general-purpose commercial products, (2) conventional programming languages, and (3) generalized water resources engineering models. Several alternative types of software may be used for a particular application. Various options may be adopted for solving the examples and end-of-chapter problems in this textbook. Different tools have certain advantages and disadvantages in various situations. Choice of software is also largely dependent on personal preferences.

1.4.1 General-Purpose Commercial Software

Much of the proliferation of software on the commercial market, which is widely used in various business, scientific, and engineering fields, is also extensively used in water resources engineering. Computer programs are dynamic with new versions being released periodically. Water resources engineers continue to discover new uses for old software, as well as for new products being marketed. Several particularly useful categories of general-purpose software packages are noted in Table 1.5, along with examples of popular products in each category.

Spreadsheet programs are used routinely by millions of businesses, professional offices, universities, and homes throughout the world. Water resources engineers have recognized the usefulness of electronic spreadsheets since the early 1980's when they were first marketed. Spreadsheet programs may be conveniently applied in solving many of the problems covered in this book. They have the advantage of applying the same familiar software to many different applications. For relatively simple applications, they are used to develop complete models. Spreadsheet packages also are commonly used as preprocessors for preparing and organizing input data for complex models and as postprocessors for summarizing, plotting, and analyzing simulation results.

Water resources engineering models are based on sets of algebraic or differential equations representing governing principles, such as conservation of mass, momentum, and energy. For fairly simple applications, model development may consist of formulating the appropriate equations and then solving them using mathematical modeling environments, such as those cited in Table 1.5. These software products provide capabilities for solving algebraic and differential equations; performing differentiation and integration, matrix operations, and statistical computations; and displaying results in numbers, tables, symbols, and graphs. The packages provide built-in mathematical and statistical functions and programming capabilities.

A geographic information system (GIS) is a set of computer-based tools for storing, processing, combining, manipulating, analyzing, and displaying data that are spatially referenced to the earth. Many types of water resources engineering models are developed within GIS environments or interconnected with GIS. A complete model may be constructed with a GIS software package, but more often the GIS serves to manage voluminous spatial input and output data for other models. Water-related spatial information managed with GIS include topographic maps, watershed characteristics (land use, vegetation, and soil types), stream configurations, floodplain delineations, geologic formations, water distribution and other utility system layouts and components, demographic data, precipitation and stream gage information, and other climatic information.

Computer-aided drafting and design (CADD) software is used for a variety of graphics applications in various fields, including water resources engineering. CADD programs provide drawing and specialized graphics capabilities used for mapping and general technical illustration purposes, as well as traditional drafting and design functions. Because CADD programs store and display spatial data, they often serve as components of GISs. An example of a CADD application is to draw complex water distribution system pipe networks.

1.4.2 Programming Languages

Many computer language translation software packages are marketed for developing application programs. Although water resources engineering models have been written in a variety of high-level languages, Fortran has dominated. Fortran (*For*mula *Tran*slator) is the oldest high-level programming language, dating back to the 1950's, and continues to be improved with new versions. It is widely used in engineering and science. The C and object-oriented C++ programming languages are also popular and provide excellent graphics capabilities, as well as optimizing computational efficiency. BASIC (*B*eginner's *A*ll-Purpose *S*ymbolic *I*nstruction *C*ode) is an example of other programming languages used in water resources engineering. Different languages are often used in combination. Visual BASIC or C may be used to develop graphical user interfaces for models with computational routines written in Fortran. Water resources engineers develop models in various versions of these languages using programming environment software products sold by a variety of companies, including those cited in Table 1.5.

Computer programs can be written fairly easily for relatively simple models. However for complex models, formulating computational algorithms, devising data management schemes, writing and debugging code, and testing new programs are very time consuming. Developing new computer programs, written in Fortran, C, C++, and/or other languages, provides flexibility in situations where other simpler options are not readily available. However, as discussed next, generalized programs have been developed for a broad spectrum of water resources engineering applications. These generalized models are extensively applied, greatly expanding the modeling and analysis capabilities of the professional water resources engineering community.

1.4.3 Generalized Water Resources Engineering Models

Most of the modeling and analysis methods covered in this textbook are incorporated in the several generalized water resources engineering models listed in Table 1.6. Sections of the book that discuss these and other similar models are cited in Table 1.6. These models are examples representative of many other similar models, also reflecting the methods presented in this book, available from the organizations listed in Table 1.7 (Wurbs, 1995, 1998). These widely applied generalized models continue to be expanded and updated, with new versions periodically being released.

TABLE 1.6 GENERALIZED WATER RESOURCES ENGINEERING MODELS

Generalized model	Model developer	Textbook section
KYPIPE Pipe Network Analysis	University of Kentucky	4.7
EPANET Pipe Network Water Quality Analysis	Environmental Protection Agency	4.7
HEC-RAS River Analysis System	Hydrologic Engineering Center	5.10
FLDWAV Flood Wave Model	National Weather Service	6.6
HEC-FFA Flood Frequency Analysis	Hydrologic Engineering Center	7.7.1
HEC-HMS Hydrologic Modeling System	Hydrologic Engineering Center	8.9.1
SWMM Stormwater Management Model	Environmental Protection Agency	8.9.2
SWAT Soil and Water Assessment Tool	Agricultural Research Service	8.9.3
BASINS Better Assessment Science Integrating Point and Nonpoint Sources	Environmental Protection Agency	8.9
MODFLOW Modular Groundwater Flow Model	U.S. Geological Survey	9.7
HEC-FDA Flood Damage Analysis	Hydrologic Engineering Center	11.3.5
HEC-RESSIM Reservoir System Simulation	Hydrologic Engineering Center	12.8.2
HEC-5 Flood Control and Conservation Systems	Hydrologic Engineering Center	12.8.2
WRAP Water Rights Analysis Package	Texas A&M University	12.8.2
MODSIM River Basin Network Flow Model	Colorado State University	12.8.2
RiverWare Reservoir and River Operations	USBR, TVA, CADSWES	12.8.2

TABLE 1.7 MODEL DEVELOPMENT AND DISTRIBUTION ORGANIZATIONS

Hydrologic Engineering Center U.S. Army Corps of Engineers Davis, California 95616 http://www.hec.usace.army.mil/	Engineering Research and Development Center U.S. Army Corps of Engineers Vicksburg, Mississippi 39180-6199 http://www.erdc.army.mil/
Water Resources Division U.S. Geological Survey Reston, Virginia 22092 http://www.usgs.gov/	Office of Hydrology National Weather Service, NOAA Silver Spring, Maryland 20910 http://www.nws.noaa.gov/
Center for Exposure Assessment Modeling National Exposure Research Laboratory U.S. Environmental Protection Agency Athens, Georgia 30613-0801 http://www.epa.gov/ceampubl/ceamhome.htm	Center for Subsurface Modeling Support Kerr Environmental Research Laboratory U.S. Environmental Protection Agency Ada, Oklahoma 74820 http://www.epa.gov/ada/csmos.html
Hydrologic Modeling Inventory U.S. Bureau of Reclamation Denver, Colorado 80225-0007 http://www.usbr.gov/hmi	National Technical Information Service Federal Computer Products Center Springfield, Virginia 22161 http://www.ntis.gov/fcpc/opd.htm
International Ground Water Modeling Center Colorado School of Mines Golden, Colorado 80401-1887 http://www.mines.edu/igwmc/	Hydrology and Water Resources Programme World Meteorological Organization Geneva 2, Switzerland http://www.wmo.ch/web/homs/hwrphome.html
Civil Engineering Software Center University of Kentucky Lexington, Kentucky 40506-0281 http://www.kypipe.com/	Haestad Methods 37 Brookside Road Waterbury, Connecticut 06708 http://www.haestad.com/

Generalized means the computer model is designed for application to a range of problems dealing with systems of various configurations and locations, rather than being developed to address a particular problem at a specific site. In applying the software package, the model user develops input for the system of concern. For example, the Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) developed by the Hydrologic Engineering Center (HEC) may be applied to essentially any watershed and river system. HEC-HMS and HEC-RAS and their predecessors, called HEC-1 and HEC-2, have been applied by cities, agencies, and consulting firms to delineate floodplains in most of the 20,000 cities participating in the NFIP, as well as in many other types of applications throughout the U.S. and abroad. The EPA's Stormwater Management Model has been applied in investigating both water quality and quantity aspects of stormwater management in numerous cities. KYPIPE and EPANET have been applied to model the hydraulics of pipe networks in numerous cities. Likewise, the widely used MODFLOW is generalized for application to essentially any groundwater aquifer.

The widely used software packages developed and distributed by the federal agencies listed in Table 1.7 are in the public domain. These generalized models required large amounts of public funds to develop, but are available to all interested users, either free-of-charge or with only nominal handling charges, and may be freely copied. Instructions for obtaining numerous software packages, documentation, and supporting information are available at the web sites listed in Table 1.7. Many of the models may be directly downloaded through the internet. Proprietary commercially marketed pipe network analysis models developed without federal support are a notable example of generalized models that must be purchased.

Computer models play important roles in all aspects of water resources engineering. A tremendous amount of work has been accomplished during the past several decades in developing powerful generalized software packages. With advances in computer technology since the 1980's, everyone working in the water resources engineering field has convenient access to desktop computers, providing all the hardware capabilities needed to execute a mighty arsenal of available models. The principles and methods presented throughout this textbook are embedded within the computer models. Application of the generalized models requires a thorough knowledge of the hydraulics, hydrology, and systems analysis concepts and techniques on which the models are built.

A word of caution is warranted regarding the use of generalized models. The danger always exists of providing the novice a weapon with which to shoot him-self/herself in the foot. Easy access to computer software does not diminish the necessity for high levels of technical knowledge and expertise. The user of off-the-shelf software must still have a thorough understanding of the computations performed by the model, and the capabilities and limitations of the model in representing real-world processes. Models must be carefully and meticulously applied with professional judgment and good common sense. Although the effectiveness and efficiency of engineering work can be greatly enhanced by exploiting the capabilities provided by readily available software, modeling still requires significant time and effort, as well as high levels of technical expertise.

Regardless of the sophistication of a generalized computer program, the quality of the modeling results for a particular application can be no better than the input data for that application. Parameter values are required for the governing equations representing the processes being modeled. A variety of other input data are also required. Calibration and verification are crucial to modeling studies.

Generalized models are used to manage data, perform computations to simulate real-world processes, and display results for various analysis applications. Design processes are typically based on iterative executions of simulation models. Computer models also play an important role in documenting and transferring knowledge. Much like textbooks and other reference books and manuals, generalized modeling packages serve to organize, record, and pass on state-of-the-art knowledge.

1.4.4 Modeling Systems

A water resources engineering modeling application often involves several software packages used in combination. For example, a river basin management application might involve a modeling system that includes a watershed runoff model used to develop runoff hydrographs and pollutant loadings for input to a reservoir/river system operation model and/or water quality model which, in turn, determines discharges and contaminant concentrations at pertinent locations. The example modeling system could also include a hydraulics model to compute flow depths and velocities. A GIS, spreadsheet program, and other data management programs are included in the modeling system to develop and manage voluminous input data; perform various statistical and graphical analyses of simulation output; and display and communicate modeling results.

The software incorporated into modeling systems can be categorized as follows:

- models that simulate real-world systems and subsystems
- user interfaces
- preprocessor programs for acquiring, preparing, checking, manipulating, managing, and analyzing model input data
- postprocessor programs for managing, analyzing, interpreting, summarizing, displaying, and communicating modeling results.

The concept of decision support systems is popular in the water management community, as well as in business, engineering, and other professional fields in general. A decision support system is a user-oriented, computer-based system that supports decision-makers in addressing unstructured problems. The general concept emphasizes:

- solving unstructured problems that require combining the judgment of human decision-makers with quantitative information
- capabilities to answer *"what if"* questions quickly and conveniently by making multiple runs of one or more models
- use of enhanced user–machine interfaces and graphical displays
- efficient management of large quantities of spatial, time series, and other data.

Decision support systems include a collection of software packages and hardware. For example, decision support systems are used for real-time flood control operations of reservoir systems. Making release decisions during a flood event is a highly unstructured problem because reservoir operations are highly dependent on operator judgment, as well as prespecified operating rules and current and forecasted stream flow, reservoir storage level, and other available data. The decision support system includes data management software; watershed runoff, stream hydraulics, and reservoir/river system operation models; a computer platform with various peripheral hardware devices; and an automated real-time hydrologic data collection system.

TABLE 1.8 HYDRAULIC MODELING PACKAGE

Program	Description	Examples
	Chapter 4: Hydraulics of Pipelines and Pipe Networks	
SIMEQ	solution of linear equations	4.13
NETWORK	linear method pipe network analysis	4.15–4.18
NETOPSIM	pipe network operation simulation	4.19(a)
NETOPCON	concentration of contaminant in water distribution system	4.19(b)
PNETUNS1	initial conditions for unsteady flow	4.22–4.23
PNETUNS2	unsteady flow in a pipe network using method of characteristics	4.22–4.23
HYRAM	simulation of hydraulic ram	4.24–4.25
	Chapter 5: Open Channel Hydraulics	
YN	normal depth in a trapezoidal channel	5.8
YC	critical depth in a trapezoidal channel	5.9
STDSTEP	standard step method water surface profile	5.18, 5.21
OPNCHNET	open channel networks	5.22
MOC	method of characteristics, unsteady flow, trapezoidal channel	5.28
MACK	MacCormack scheme, unsteady flow, trapezoidal channel	5.28
MACKS	MacCormack scheme, unsteady flow, channels in series	5.29
	Chapter 6: Flood Routing	
RESROUTE	hydrologic reservoir routing	6.1, 6.2
KINRT	kinematic routing of overland flow	6.3
HYRT	hydraulic routing through a trapezoidal channel	6.4
HYRT2	hydraulic routing through trapezoidal channels in series	6.4
HYRT3	hydraulic routing through natural channels in series	6.4
HYRTIMP	hydraulic routing with implicit Preissman scheme	6.5
HYRTI	routing with implicit scheme and a pointer matrix	6.5
HYRTEDB	explicit hydraulic routing of dam break flood wave in a natural channel	6.6
HYRTEDBS	HYRTEDB with submerged weir	6.6
HYRTIDB	implicit hydraulic routing of a dam break flood wave in a natural channel	6.6
HYRTIDBS	HYRTIDB with submerged weir	6.6
HYRTWD1	program one of two for watershed routing	6.7
HYRTWD2	hydraulic routing in a branching channel watershed system	6.7
	Chapter 9: Groundwater Engineering	
WELLU	table of values for the well function u	9.10
CJAQTEST	Cooper–Jacob method of pump test analysis	9.11
SEEPAG2D	two-dimensional steady seepage analysis	9.15
THOM1DU	one-dimensional unsteady unconfined aquifer with Thomas Algorithm	9.16
ADI2DC	two-dimensional unsteady confined with ADI method	9.17
ADI2DU	two-dimensional unsteady unconfined with ADI method	9.17
GS2DU	two-dimensional unsteady unconfined with Gauss–Seidel method	9.17
PLUME2D	two-dimensional unsteady relative concentration from a continuous point source	9.18
	Chapter 10: Urban Stormwater Management	
DETENT	detention basin analysis with the unit hydrograph methodology	10.10
WATERSHD	regional detention basin analyses with the unit hydrograph methodology	10.11
HYWEIR	hydraulic routing in a trapezoidal channel with a side channel weir	10.12
CHANNEL	data for open channel design curves	10.18

Water resources engineering models are often components of decision support systems. The models are even more often applied in other planning, design, and resource management situations that do not exhibit all the characteristics attributed above to decision support systems. The relationships between analysis strategies, design and other decision-making processes, and modeling systems vary, depending on the particular water resources engineering application.

1.4.5 Hydraulic Modeling Package

The *Hydraulic Modeling Package (HMP)* is a set of Fortran programs listed in Table 1.8, developed in conjunction with Chapters 4–6, 9, and 10 of this textbook. The programs implement the computational methods outlined in these chapters and are introduced through application in the example problems listed in Table 1.8. Source code, executable programs, and example data sets are available from the Prentice Hall companion web site for this book found at http://www.prenhall.com.

These Fortran programs can be extremely useful in mastering the techniques presented in the book, particularly those methods involving numerical solutions of hydraulic equations. These relatively small programs focus on specific computational methods. Students/engineers can work directly with the code to develop a step-by-step understanding of the algorithms. You can experiment with solution schemes by changing and expanding the programs. The programs are provided primarily as a supplemental option for use in learning computational hydraulics. However, they also provide a starting point for developing your own models for research studies or practical applications.

1.5 UNITS OF MEASURE

The metric system of units is the standard adopted by most countries. The metric system has evolved from its roots in France in the 1790's to its current version known as SI units (Système Internationale d'Unites). The United States is the only major country in the world that still uses the English (U.S. customary or British Gravitational, BG) system. Although the English system of units began in England in the 1200's, England now uses the metric system. The U.S. Congress passed the Metric Conversion Act in 1975, which called for a voluntary change to the metric system. This Act was amended in 1988, making the metric system the preferred system of weights and measures for U.S. trade and commerce and requiring federal agencies to switch to the metric system for business-related activities. The federal water agencies are shifting toward the metric system. However, the English system still dominates throughout the U.S. water management community. Literature and data compiled over many decades, as well as current practice, are based on English units. Water resources engineers working in the U.S. must be familiar with both systems.