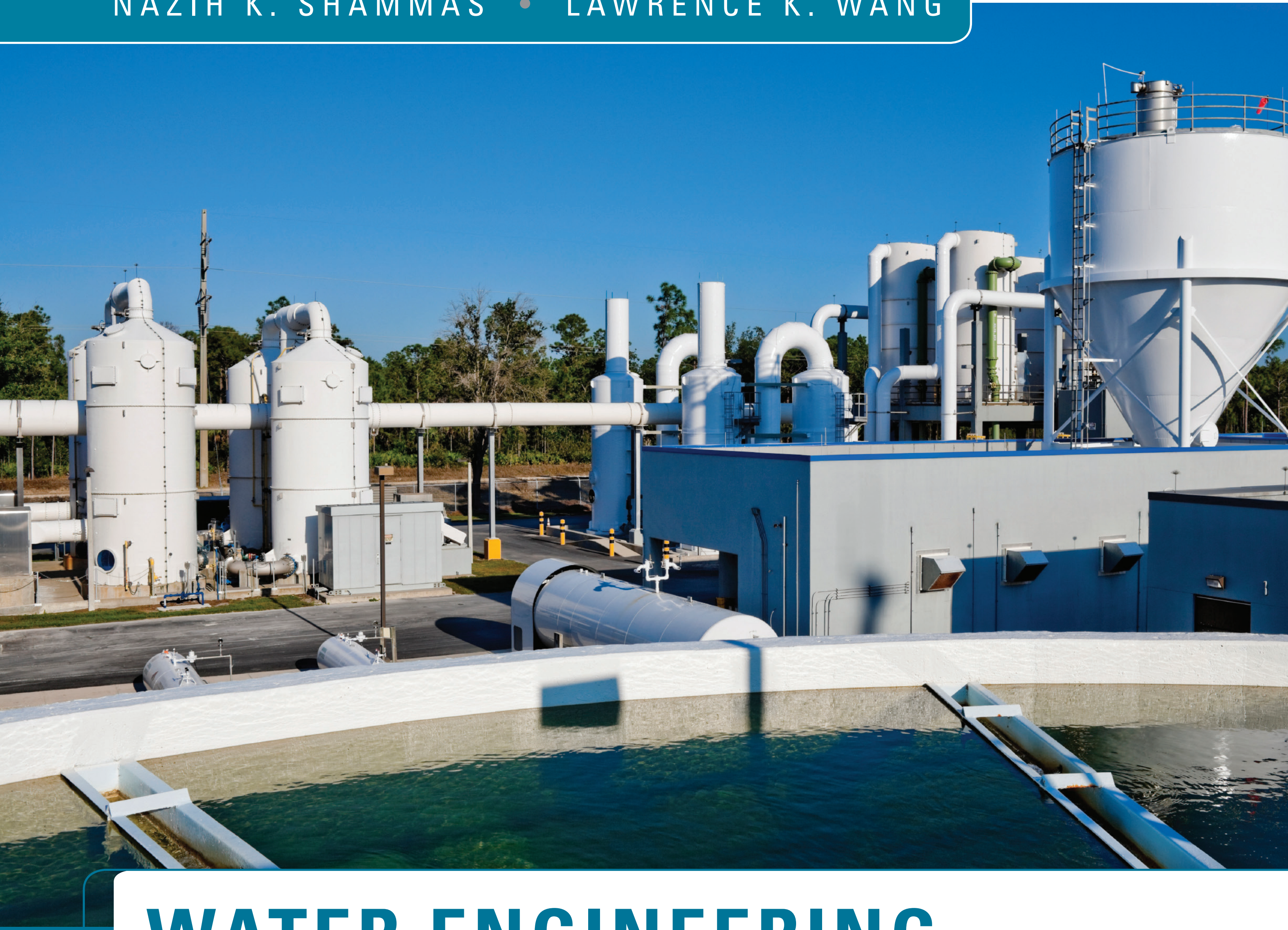
NAZIH K. SHAMMAS • LAWRENCE K. WANG



WATER ENGINEERING

Hydraulics, Distribution and Treatment

CourseSmart

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Water Engineering

Water Engineering

Hydraulics, Distribution and Treatment

First Edition

Nazih K. Shammas

University of Michigan, Ann Arbor, MI, USA (Ph.D.)
N.K.Shammas@Gmail.com

Lawrence K. Wang

Rutgers University, New Brunswick, NJ, USA (Ph.D.)
LawrenceKWang@Gmail.com

WILEY

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Preface

History of this Book Series: Water and Wastewater Engineering

This book, *Water Engineering*, is the second textbook in the *Water and Wastewater Engineering* series, which is a revision of the classic text, originally authored by Professors Gordon M. Fair (Harvard University), John C. Geyer (John Hopkins University), and Daniel A. Okun (University of North Carolina). Professors Daniel A. Okun and Marvin L. Granstorm (Rutger University) were the driving forces of this new global edition that includes both US and SI design equations and examples. The current authors, Professors Nazih K. Shammas and Lawrence K. Wang were the students of Professor Okun, and Professor Granstorm, respectively. Just before beginning the preparation of this new edition of *Water and Wastewater Engineering,* the last surviving member of the original authors, Professor Daniel A. Okun, died on December 10, 2007. In the normal course of events Professor Okun would have been with the current authors in preparing this book series. This new book series is dedicated to the memory of Professors Fair, Geyer, Okun, and Granstrom.

Goals of this Book: Water Engineering

Today, effective design and efficient operation of water engineering works ask, above all, for a fuller understanding and application of scientific principles. Thus, the results of scientific research are being incorporated with remarkable success in new designs and new operating procedures. Like other fields of engineering, water engineering has its science and its art. To reach the audience to which this book is addressed, the science of water engineering is given principal emphasis. However, the art of water engineering is not neglected. Enough elements of water engineering practice, experience, common sense, and rules of thumb are included to keep the reader aware of the water environment and constructions that place water at the service of cities and towns, and of villages and homesteads.

Further Study in Addition to Classroom Education

The study of scientific principles is best accomplished in the classroom; the application of these principles follows as a matter of practice. To further bridge the way from principle to practice, we suggest that the study of these textbooks be supplemented by (1) visits to water works, (2) examination of plans and specifications of existing water systems, (3) readings in the environmental science and engineering periodicals, (4) study of the data and handbook editions of trade journals, (5) examination of the catalogs and bulletins of equipment manufacturers, and (6) searching for the latest water engineering developments from the Internet.

Intended Audience

Like its forerunners, this new book, *Water Engineering*, is intended for students of civil and environmental engineering, no matter whether they belong to the student body of a university or are already established in their profession. Specifically, the target audience is engineering students who have had introductory calculus, chemistry and fluid mechanics, typically civil, environmental and water resources engineering majors. Several chapters of the book contain introductory material appropriate for juniors as well as more advanced material that might only be appropriate for upper-level undergraduate engineering students. Specifically, applied hydrology, hydraulics, and pertinent physical, chemical, and biological properties of water are reviewed. The inclusion of this material makes this book important also to physical and investment planners of urban and regional developments. In this sense, too, this book and other books in the new series should be of interest to chemical engineers, geologists, chemists, and biologists who are collaborators of the water environment.

Course Suggestions

The book is comprehensive and covers all aspects of water including its quality, sources, supply, drinking water standards, treatment, transmission, storage, and distribution. This comprehensive coverage gives faculty the flexibility of choosing the material as they find fit for their courses, and this wide coverage is helpful to water engineers in their everyday practice.

Courses where this book may be used include

1. Water engineering
2. Water supply, transmission and distribution system
3. Water treatment
4. Design of water treatment plants
5. Design of water distribution networks
6. Civil and sanitary engineering design
7. Environmental engineering design
8. Hydraulics
9. Water resources engineering

Key Features of This Book

Several items unique to this textbook include

1. **Solved problems.** A reliable problem-solving experience for students is carried out throughout the text and demonstrated in every example problem to reinforce best practices.
2. **Photos and illustrations.** Photos and illustrations are used throughout the text to clarify water engineering infrastructure systems and show examples of built and constructed water supply, transmission, treatment, storage and distribution facilities.
3. **Current water treatment and infrastructure issues.** Current infrastructure and global issues are addressed in the text. Examples of such issues include (a) established water treatment technologies; (b) conventional and new pathogenic microorganisms and impurities; (c) *Cryptosporidium*, volatile organic compounds, heavy metals, and disinfection by-products control; (d) flotation, membrane filtration, and UV; (e) groundwater under the direct influence of surface water; (f) dual water systems; (g) cross-connections control and backflow prevention; (h) design nomograms for fast water infrastructure analysis; (i) computer-aided water distribution system modeling and analysis; (j) water safety and emergency response.
4. **Engineering equations and example problems with both US and SI Units for training engineers to work globally.** The text has a multitude of examples and problems. Such problems incorporate both SI and the more customary US unit systems. We feel that most other texts fall short in both these areas by not providing students with examples that help explain difficult technical concepts and by only focusing on one system of units.
5. **Applied hydraulics.** Hydraulics concepts are critical for the civil, environmental and water resources engineering professionals, and thus the readers. Applied hydraulics topics such as pumps, weirs, pressurized pipe flow, gravity flow, head losses are reviewed in this book for practical design of water-handling facilities.
6. **Prevention through design, residuals management, and water system safety.** Chapter 23 is dedicated to prevention through design (PtD), as it is important for readers to learn about this new strategy. NIOSH is promoting the inclusion of PtD in undergraduate engineering education, has reviewed this chapter and provided the illustrative case studies described in Chapter 6, Water Distribution Systems: Components, Design, and Operation, and Chapter 22, Residues Management, Safety, and Emergency Response. Other water engineering texts do not address these important topics.

Instructor Resources

The following resources are available to instructors on the book website at:

1. **Solutions manual.** Complete solutions for every homework problem and answers to all discussion questions in the text will be available to instructors.
2. **Image gallery.** Images from the text in electronic format, for preparation of lecture PowerPoint slides.
3. **Access to student resources.** Instructors will also have access to all the student resources.

The instructor resources are password protected, and will be made available to instructors who have adopted the text for their course. Visit the instructor section of the website to register for a password.

Student Resources

The following resources are available to students on the book website at:

1. **Data sets.** Data sets for all examples and homework exercises in the text will be provided, so that students may perform what-if scenarios, and to avoid errors due to data entry during problem solving.
2. **Access to design software.** Included with the text, so students may download the software from an online source.

Software

Included with this text is access to the software Haestad Methods Water Solutions by Bentley. Software exhibited in the text, include **WaterGEMS** that is used to illustrate the application of various available software programs in helping civil and environmental engineers design and analyze water distribution systems. It is also used by water utility managers as a tool for the efficient operation of distribution systems. See Chapter 7, Water Distribution Systems: Modeling and Computer Applications.

Acknowledgments

Books do not come off the press through the efforts of authors alone. Their preparation passes successively through editorial and production stages. The authors would like to thank our colleagues, mentors, Wiley editors/reviewers Michael Leventhal and Bob Esposito, and the resource providers and designers who have guided our efforts along these ways.

Sincere appreciations are extended to the families of Professors Fair, Geyer, Okun, and Granstrom, and the reviewers whose suggestions and comments have significantly improved the overall quality of this book series.

We also thank Dr. Richard Rinehart, Prevention through Design National Initiative at NIOSH, who reviewed PtD (Chapter 23), and Dr. Carolyn M. Jones (SFPUC Health and Safety Program Manager at NIOSH), who provided the case studies included in Chapters 6 and 22.

A book is not written in long evenings and on holidays without the consent, encouragement, and cooperation of the writers' families. This, too, should be a matter of record.

Nazih K. Shammas
American University of Beirut, Lebanon (BE)
University of North Carolina at Chapel Hill, NC, USA (MSSE)
University of Michigan, Ann Arbor, MI, USA (PhD)

Lawrence K. Wang
National Cheng Kung University, Tainan, Taiwan, ROC (BSCE)
Missouri University of Science and Technology, Rolla, MO, USA (MSCE)
University of Rhode Island, Kingston, RI, USA (MS)
Rutgers University, New Brunswick, NJ, USA (PhD)

Chapter 1

Introduction to Water Systems

The right to water is an implicit part of the right to an adequate standard of living and the right to the highest attainable standard of physical and mental health, both of which are protected by the United Nations' *International Covenant on Economic, Social and Cultural Rights,* which was established in 1976. However, some countries continue to deny the legitimacy of this right. In light of this fact and because of the widespread noncompliance of states with their obligations regarding the right to water, the United Nations' Committee on Economic, Social and Cultural Rights confirmed and further defined the right to water in its General Comment No. 15 in 2002. The comment clearly states that the right to water emanates from and is indispensable for an adequate standard of living as it is one of the most fundamental conditions for survival:

> *The human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses. An adequate amount of safe water is necessary to prevent death from dehydration, reduce the risk of water-related disease and provide for consumption, cooking, personal and domestic hygienic requirements.*

According to the World Health Organization (WHO), 1.1 billion people (17% of the global population) lack access to safe drinking water, meaning that they have to revert to unprotected wells or springs, canals, lakes, or rivers to fetch water; 2.6 billion people lack adequate sanitation; and 1.8 million people die every year from diarrheal diseases, including 90% of children under age 5. This situation is no longer bearable. To meet the WHO's *Water for Life Decade (2005–2015)*, an additional 260,000 people per day need to gain access to improved water sources.

In 2004 about 3.5 billion people worldwide (54% of the global population) had access to piped water supply through house connections. Another 1.3 billion (20%) had access to safe water through other means than house connections, including standpipes, "water kiosks," protected springs, and protected wells.

In the United States 95% of the population that is served by community water systems receives drinking water that meets all applicable health-based drinking water standards through effective treatment and source water protection. In 2007, approximately 156,000 US public drinking water systems served more than 306 million people. Each of these systems regularly supplied drinking water to at least 25 people or 15 service connections. Beyond their common purpose, the 156,000 systems vary widely. Table 1.1 groups water systems into categories that show their similarities and differences. For example, the table shows that most people in the United States (286 million) get their water from a community water system. Of the approximately 52,000 community water systems, just 8% of those systems (4048) serve 82% of the people.

Water is used in population centers for many purposes: (a) for drinking and culinary uses; (b) for washing, bathing, and laundering; (c) for cleaning windows, walls, and floors; (d) for heating and air conditioning; (e) for watering lawns and gardens; (f) for sprinkling and cleaning streets; (g) for filling swimming and wading pools; (h) for display in fountains and cascades; (i) for producing hydraulic and steam power; (j) for employment in numerous and varied industrial processes; (k) for protecting life and property against fire; and (l) for removing offensive and potentially dangerous wastes from households, commercial establishments, and industries. To provide for these varying uses, which total about 100 gallons per capita per day (gpcd) or 378 liters per capita per day (Lpcd) in average North American *residential* communities and 150 gpcd (568 Lpcd) or more in large *industrial* cities, the supply of water must be satisfactory in quality and adequate in quantity, readily available to the user, relatively cheap, and easily disposed of after it has served its many purposes. Necessary engineering works are waterworks, or water supply systems, and wastewater works, or wastewater management systems.

Waterworks withdraw water from natural sources of supply, purify it if necessary, and deliver it to the consumer. Wastewater works collect the spent water of the community—about 70% of the water supplied—together with varying amounts of entering ground and surface waters.

Water Engineering: Hydraulics, Distribution and Treatment, First Edition. Nazih K. Shammas and Lawrence K. Wang.

Table 1.1 US public water systems size by population served in 2007

Water system		Very small (500 or less)	Small (501–3,300)	Medium (3,301–10,000)	Large (10,001–100,000)	Very large (>100,000)	Total
Community water system[a]	No. of systems	29,282	13,906	4,822	3,702	398	52,110
	Population served	4,857,007	19,848,329	27,942,486	105,195,727	128,607,655	286,451,204
	Percentage of systems	56	27	9	7	1	100
	Percentage of population	2	7	10	37	45	100
Nontransient noncommunity water system[b]	No. of systems	16,034	2,662	120	22	1	18,839
	Population served	2,247,556	2,710,330	639,561	533,845	203,000	6,334,292
	Percentage of systems	85	14	1	0	0	100
	Percentage of population	35	43	10	8	3	100
Transient noncommunity water system[c]	No. of systems	81,873	2,751	102	15	3	84,744
	Population served	7,230,344	2,681,373	546,481	424,662	2,869,000	13,751,860
	Percentage of systems	97	3	0	0	0	100
	Percentage of population	53	19	4	3	21	100
Total no. of systems		127,189	19,319	5,044	3,739	402	155,693

Source: Courtesy US Environmental Protection Agency.

[a] Community water system: a public water system that supplies water to the same population year-round.

[b] Nontransient noncommunity water system: a public water system that regularly supplies water to at least 25 of the same people at least 6 months per year, but not year-round. Some examples are schools, factories, office buildings, and hospitals that have their own water systems.

[c] Transient noncommunity water system: a public water system that provides water in a place such as a gas station or campground where people do not remain for long periods of time.

The collected wastewaters are treated and reused or discharged, usually into a natural water body, more rarely onto land. Often the receiving body of water continues to serve also as a source of important water supplies for many purposes. It is this multiple use of natural waters that creates the most impelling reasons for sound water quality management.

1.1 COMPONENTS OF WATER SYSTEMS

Each section of this chapter offers, in a sense, a preview of matters discussed at length in later parts of this book. There they are dealt with as isolated topics to be mastered in detail. Here they appear in sequence as parts of the whole so that their general purpose and significance in the scheme of things may be understood and may give reason for closer study.

Municipal water systems generally comprise (a) *collection works*, (b) *purification works*, (c) *transmission works*, and (d) *distribution works*. The relative functions and positions of these components in a surface water supply are sketched in Fig. 1.1. Collection works either tap a source continuously adequate in volume for present and reasonable future demands or convert an intermittently insufficient source into a continuously adequate supply. To ensure adequacy, seasonal and, in large developments, even annual surpluses must be stored for use in times of insufficiency. When the quality of the water collected is not satisfactory, purification works are introduced to render it suitable for the purposes it must serve: contaminated water is disinfected; aesthetically displeasing water made attractive and palatable; water containing iron or manganese deferrized or demanganized; corrosive water deactivated; and hard water softened. Transmission works convey the collected and purified supply to the community, where distribution works dispense it to consumers in wanted volume at adequate pressure. Ordinarily, the water delivered is metered so that an equitable charge can be made for its use and, often, also for its disposal after use.

1.2 REQUIRED CAPACITY

Water supply systems are designed to meet population needs for a reasonable number of years in the future. The rate of consumption is normally expressed as the mean annual use in gpcd or Lpcd, and seasonal, monthly, daily, and hourly departures in rate are given in percentages of the mean. In North America the spread in consumption is large: from

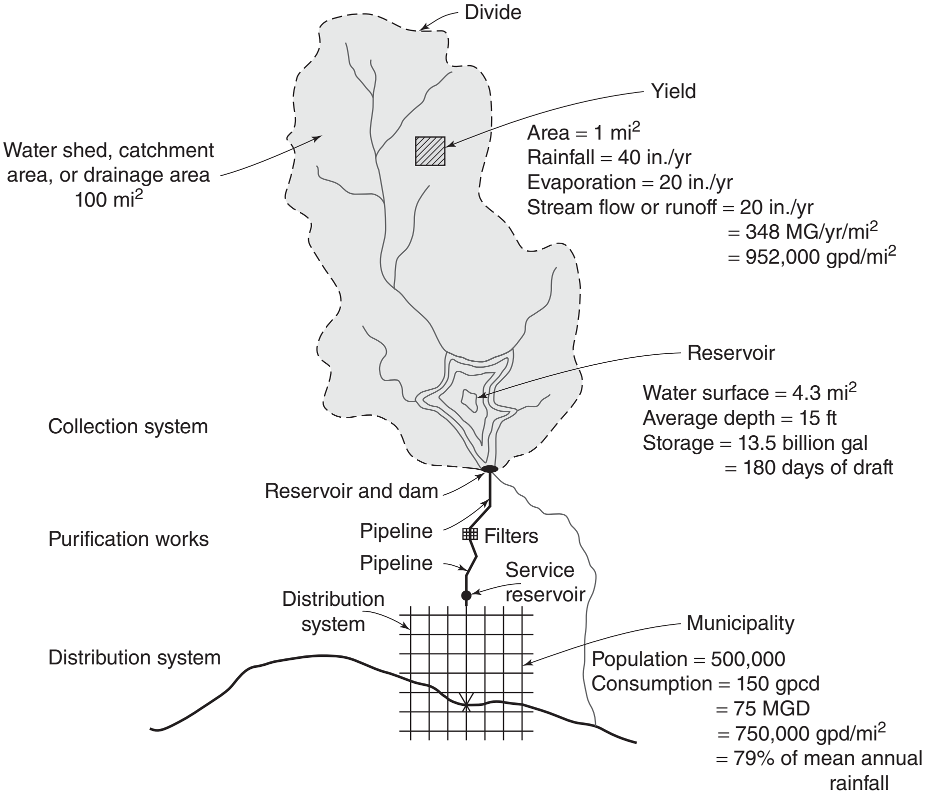

Figure 1.1 Rainfall, runoff, storage, and draft relations in the development of surface water (conversion factors: 1 mi^2 = 2.59 km^2; 1 in./yr = 25.4 mm/yr; 1 ft = 0.3048 m; 1 MG/yr/mi^2 = 1.46 ML/yr/km^2; 1 gpd/mi^2 = 1.461 L/d/km^2; 1 billion gal = 1 BG = 3.785 billion L = 3.785 BL; 1 gpcd = 3.785 Lpcd; 1 MGD = 3.785 MLD).

35 to 500 gpcd (132–1890 Lpcd), varying radically with industrial water demands. Average rates between 100 and 200 gpcd (378–757 Lpcd) are common, and a generalized average of 150 gpcd (568 Lpcd) is a useful guide to normal requirements.

The capacity of individual system components is set by what is expected of them. Distribution systems, for example, must be large enough to combat and control serious conflagrations without failing to supply maximum *coincident* domestic and industrial drafts. Fire demands vary with size and value of properties to be protected and are normally a function of the gross size of the community. The distribution system leading to the high-value district of an average American city of 100,000 people, for example, must have an excess of *fire standby* capacity equal in itself to the average rate of draft. For smaller or larger American communities, the standby capacity falls or rises, within certain limits, more or less in proportion to the square root of the population.

1.3 SOURCES OF WATER SUPPLY

The source of water commonly determines the nature of the collection, purification, transmission, and distribution works. Common sources of freshwater and their development are as follows:

1. *Rainwater*:
   (a) From roofs, stored in cisterns, for small individual supplies.
   (b) From larger, prepared watersheds, or catches, stored in reservoirs, for large communal supplies.
2. *Surface water*:
   (a) From streams, natural ponds, and lakes of sufficient size, by continuous draft.
   (b) From streams with adequate flood flows, by intermittent, seasonal, or selective draft of clean floodwaters, and their storage in reservoirs adjacent to the streams, or otherwise readily accessible from them.
   (c) From streams with low dry-weather flows but sufficient annual discharge, by continuous draft through storage of necessary flows in excess of daily use in one or more reservoirs impounded by dams thrown across the stream valleys.
   (d) From brackish and seawater by desalination. Desalination is an artificial process by which saline water is converted to freshwater. The most common desalination processes are distillation and reverse osmosis. Desalination is currently expensive compared to most alternative sources of water, and only a small fraction of total human use is satisfied by desalination. It is only economically practical for high-valued uses (such as household and industrial uses) in arid areas. The most extensive use is in the Persian (Arabian) Gulf. Mildly saline waters (brackish) are desalted most economically by reverse osmosis;

strongly saline waters by evaporation and condensation.

3. *Groundwater*:
   - (a) From natural springs.
   - (b) From wells.
   - (c) From infiltration galleries, basins, or cribs.
   - (d) From wells, galleries, and, possibly, springs, with flows augmented from some other source (i) spread on the surface of the gathering ground, (ii) carried into charging basins or ditches, or (iii) led into diffusion galleries or wells.
   - (e) From wells or galleries with flows maintained by returning to the ground the water previously withdrawn from the same aquifer for cooling or similar purposes.

Several schemes have been proposed to make use of *icebergs* as a water source; to date, however, this has only been done for novelty purposes. One of the serious moves toward the practical use of icebergs is the formation of an Arabian–American investment group to search for the optimal way to transport and melt icebergs for use as a source of drinking water supply without the need for on-land storage. Glacier runoff is considered to be surface water.

An iceberg is a large piece of freshwater ice that has broken off from a snow-formed glacier or ice shelf and is floating in open water. Because the density of pure ice is about 920 kg/m^3 and that of sea water about 1025 kg/m^3, typically only one-tenth of the volume of an iceberg is above water. The shape of the rest of the iceberg under the water can be difficult to surmise from looking at what is visible above the surface. Icebergs generally range from 1 to 75 m (about 3–250 ft) above sea level and weigh 100,000–200,000 metric tonne (about 110,000–220,000 short ton). The tallest known iceberg in the North Atlantic was 168 m (about 551 ft) above sea level, making it the height of a 55 story building. Despite their size, icebergs move an average of 17 km (about 10 mi) a day. These icebergs originate from glaciers and may have an interior temperature of –15°C to −20°C (5°F to − 4°F).

Municipal supplies may be derived from more than one source, the yields of available sources ordinarily being combined before distribution. *Dual public water supplies* (see Chapter 8) of unequal quality are unusual in North America. However, they do exist, for example, as a high-grade supply for general municipal uses and a low-grade supply for specific industrial purposes or firefighting. Unless the low-grade (nonpotable) supply is rigorously disinfected, its existence is frowned on by health authorities because it may be cross-connected, wittingly or unwittingly, with the high-grade (potable) supply. A *cross-connection* is defined as a junction between water supply systems through which water from doubtful or unsafe sources may enter an otherwise safe supply.

1.4 RAINWATER

Rain is rarely the immediate provenance of municipal water supplies. Instead, the capture of rainwater is confined to farms and rural settlements usually in semiarid regions devoid of satisfactory ground or surface waters. On homesteads, rainwater running off roofs is led through gutters and downspouts to rain barrels or cisterns situated on or in the ground. Storage transforms the intermittent rainfall into a continuous supply. For municipal service, sheds or catches on ground that is naturally impervious or made tight by grouting, cementing, paving, or similar means must usually be added.

The gross yield of rainwater is proportional to the receiving area and the amount of precipitation. However, some rain

EXAMPLE 1.1 CALCULATING THE VOLUME OF RAINFALL THAT CAN BE COLLECTED FROM A BUILDING ROOF

Make a rough estimate of the volume in gallons or liters of water that can be caught by 3,000 ft^2 (278.7 m^2) of horizontally projected roof area (the average area of American farm buildings) in a region where the mean annual rainfall is 15 in. (38.1 cm).

Solution 1 (US Customary System):

Gross yield = 3,000 ft^2 × (15/12 ft) × 7.48 gal/ft^3 = 28,100 gal annually = 28,100 gal/365 days
= 77 gpd.

Net yield approximates two-thirds gross yield = 18,800 gal annually = **51 gpd**.

About half the net annual yield, or 9,400 gal = 1,250 ft^3, must normally be stored to tide the supply over dry spells.

Solution 2 (SI System):

Gross yield = (278.7 m^2)(38.1/100 m)(1,000 L/m^3) = 106,178 L annually = 291 L/day
= 291 L/d.

Net yield approximates two-thirds gross yield = 291 L/d (2/3) = **194 L/d** = 70,790 L/year.

About half the net annual yield = 0.5 (70,790 L/year) = 35,395 L = 35.4 m^3 must be stored to tide the supply over dry spells.

is blown off the roof, evaporated, or lost in wetting the collecting surfaces and conduits and in filling depressions or improperly pitched gutters. Also, the first flush of water may have to be wasted because it contains dust, bird droppings, and other unwanted materials. The combined loss may be high. A cutoff, switch, or deflector in the downspout permits selective diversion of unwanted water from the system. Sand filters will cleanse the water as it enters the cistern and prevent its deterioration via the growth of undesirable organisms and consequent tastes, odors, and other changes in attractiveness and palatability.

The storage to be provided in *cisterns* depends on the distribution of rainfall. Storage varies with the length of dry spells and commonly approximates one-third to one-half the annual consumption. If rainfalls of high intensity are to be captured, standby capacity must exist in advance of filtration. Because their area is small, roofs seldom yield much water. A careful analysis of storm rainfalls and seasonal variations in precipitation is, therefore, required.

1.5 SURFACE WATER

In North America by far the largest volumes of municipal water are collected from surface sources. The quantities that can be gathered vary directly with the size of the catchment area, or watershed, and with the difference between the amounts of water falling on it and the amounts lost by evapotranspiration. The significance of these relationships to water supply is illustrated in Fig. 1.1. Where surface water and groundwater sheds do not coincide, some groundwater may enter from neighboring catchment areas or escape to them.

1.5.1 Continuous Draft

Communities on or near streams, ponds, or lakes may take their supplies from them by continuous draft if stream flow and pond or lake capacity are high enough at all seasons of the year to furnish requisite water volumes. Collecting works ordinarily include (a) an intake crib, gatehouse, or tower; (b) an intake conduit; and (c) in many places, a pumping station. On small streams serving communities of moderate size, an intake or diversion dam may create sufficient depth of water to submerge the intake pipe and protect it against ice. From intakes close to the community the water must generally be lifted to purification works and thence to the distribution system.

Most large streams are polluted by wastes from upstream communities and industries. Purification of their waters is then a necessity. Cities on large lakes usually guard their supplies against their own and their neighbor's wastewater and spent industrial-process waters by moving their intakes far away from shore and purifying both their water and wastewater. Diversion of wastewater from lakes will retard the lakes' eutrophication.

1.5.2 Selective Draft

Low stream flows are often left untouched. They may be wanted for other downstream purposes or they may be too highly polluted for reasonable use. Only clean floodwaters are then diverted into reservoirs constructed in meadow lands adjacent to the stream or otherwise conveniently available. The amount of water so stored must supply demands during seasons of unavailable stream flow. If draft is confined to a quarter year, for example, the reservoir must hold at least three-fourths of the annual supply. In spite of its selection and long storage, the water may have to be purified.

1.5.3 Impoundage

In their search for clean water and water that can be brought and distributed to the community by gravity, engineers have developed supplies from upland streams. Most of them are tapped near their source in high and sparsely settled regions. To be of use, their annual discharge must equal or exceed the demands of the community they serve for a reasonable number of years in the future. Because their dry season flows generally fall short of concurrent municipal requirements, their floodwaters must usually be stored in sufficient volume to ensure an adequate supply. Necessary reservoirs are impounded by throwing dams across the stream valley. In this way, amounts up to the mean annual flow can be utilized. The area draining to an impoundment is known as the catchment area or watershed. Its economical development depends on the value of water in the region, but it is a function, too, of runoff and its variation, accessibility of catchment areas, interference with existing water rights, and costs of construction. Allowances must be made for evaporation from new water surfaces generated by the impoundage (Fig. 1.2) and also often for release of agreed-on flows to the valley below the dam (compensating water). Increased ground storage in the flooded area and the gradual diminution of reservoir volumes by siltation must also be considered.

Intake structures are incorporated in impounding dams or kept separate. Other important components of impounding reservoirs are (a) spillways safely passing floods in excess of reservoir capacity and (b) diversion conduits safely carrying the stream past the construction site until the reservoir has been completed and its spillway can go into action. Analysis of flood records enters into the design of these ancillary structures.

Some impounded supplies are sufficiently safe, attractive, and palatable to be used without treatment other than protective disinfection. However, it may be necessary to remove high color imparted to the stored water by the decomposition of organic matter in swamps and on the flooded valley bottom; odors and tastes generated in the decomposition or growth of algae, especially during the first years after filling; and turbidity (finely divided clay or silt) carried into streams or reservoirs by surface wash, wave action, or bank

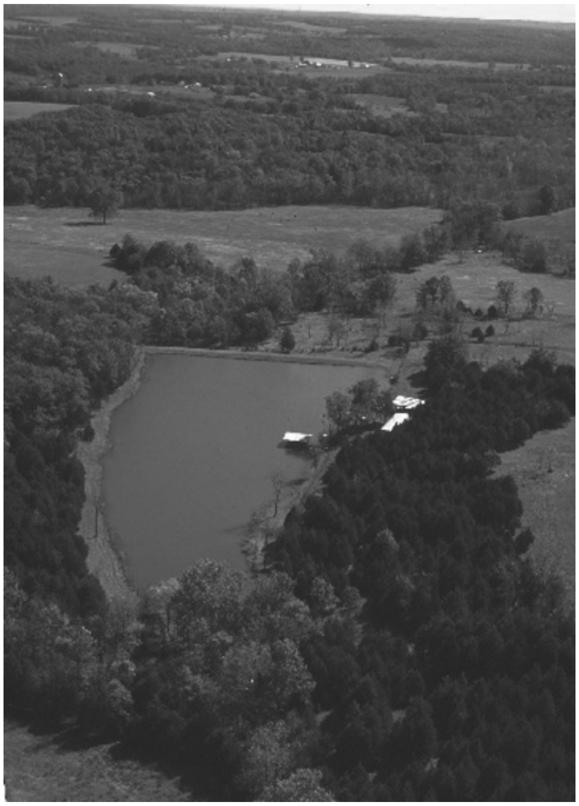

Figure 1.2 A watershed lake in Western Missouri provides water supply (Courtesy of the National Resources Conservation Service and USDA).

erosion. Recreational uses of watersheds and reservoirs may call for treatment of the flows withdrawn from storage.

Much of the water in streams, ponds, lakes, and reservoirs in times of drought, or when precipitation is frozen, is seepage from the soil. Nevertheless, it is classified as surface runoff rather than groundwater. Water seeps *from* the ground when surface streams are low and *to* the ground when surface streams are high. Release of water from ground storage or from accumulations of snow in high mountains is a determining factor in the yield of some catchment areas. Although surface waters are derived ultimately from precipitation, the relations between precipitation, runoff, infiltration, evaporation, and transpiration are so complex that engineers rightly prefer to base calculations of yield on available stream gaugings. For adequate information, gaugings must extend over a considerable number of years.

1.6 GROUNDWATER

Smaller in daily delivery, but many times more numerous than surface water supplies, are the municipal and private groundwater supplies of North America. Groundwater is drawn from many different geological formations: (a) from the pores of alluvial (water-borne), glacial, or aeolian (wind-blown) deposits of granular, unconsolidated materials such as sand and gravel, and from consolidated materials such as sandstone; (b) from the solution passages, caverns, and cleavage planes of sedimentary rocks such as limestone, slate, and shale; (c) from the fractures and fissures of igneous rocks; and (d) from combinations of these unconsolidated and consolidated geological formations. Groundwater sources, too, have an intake or catchment area, but the catch, or recharge, is by infiltration into soil openings rather than by runoff over its surface. The intake area may be nearby or a considerable distance away, especially when flow is confined within a water-bearing stratum or *aquifer* (from Latin *aqua*, "water," and *ferre*, "to bear") underlying an impervious stratum or *aquiclude* (from Latin *aqua*, "water," and *cludere*, "to shut" or "to close out").

EXAMPLE 1.2 ESTIMATES OF YIELDS FROM WATERSHEDS AND STORAGE REQUIREMENTS

Certain rough estimates of the yield of surface watersheds and storage requirements are shown in Fig. 1.1. Rainfall is used as the point of departure, merely to identify the dimensions of possible rainfall–runoff relationships. Determine

1. The yields from the watersheds,
2. The storage requirements,
3. The number of people who can be supported by a drainage area of 100 mi^2 (259 km^2) if there is adequate impoundage for water storage, and
4. The number of people who can be supported by a drainage area of 100 mi^2 (259 km^2) if there is no impoundage for water storage.

The following assumptions are made: (a) rainfall $= 20$ in./km^2 annually $= 19.6$ cm/km^2, (b) a stream flow of about 1 MGD/km^2 (million gallons per day per square mile) or (1.547 ft^3/s)/km^2 [or 1.46 MLD/km^2 (million liters per day per square kilometer)] is a good average for the well-watered sections of North America, (c) for 75% development (0.75×1 MGD/km^2 or 0.75×1.46 MLD/km^2), about half a year's supply must generally be stored. In semiarid regions storage of three times the mean annual stream flow is not uncommon, that is, water is held over from wet years to supply demands during dry years, (d) average water consumption = 150 gpcd = 567.8 Lpcd, (e) for water supply by continuous draft, low water flows rather than average annual yields govern. In well-watered sections of North America, these approximate 0.1 ft^3/s or 64,600 gpd/km^2 (or 28.32 L/s, or 0.094316 MLD/km^2).

Solution 1 (US Customary System):

1. The following conversion factors and approximations are being employed:

   1 in. rainfall/km^2 = 17.378 MG

   Hence, 20 in./km^2 annually = 20 × 17.378 = 348 MG or 348/365 = **0.952 MGD**.

2. A stream flow of about 1 MGD/km^2 is a good average for the well-watered sections of North America. Not all of it can be adduced economically by storage.

   For 75% development (0.75 MGD/km^2, or 750,000 gpd/km^2), about half a year's supply must generally be stored. For a catchment area of 100 km^2, therefore

   Storage = (0.75 MGD/km^2)(100 km^2) × (0.5 × 365 days) = 13,688 MG = **13.5 BG** (billion gallons) approximately.

   In semiarid regions storage of three times the mean annual stream flow is not uncommon, that is, water is held over from wet years to supply demands during dry years.

3. For an average consumption of 150 gpcd, the drainage area of 100 km^2 and impoundage of 13.5 BG will supply a population of 100 × 750,000/150 = **500,000 persons**.

4. For water supply by continuous draft, low water flows rather than average annual yields govern.

   In well-watered sections of North America, these approximate 0.1 ft^3/s or 64,600 gpd/km^2.

   A catchment area of 100 km^2, therefore, can supply without storage

   100 × 64,600/150 = **43,000 people**.

   This is compared against 500,000 people in the presence of proper storage.

Solution 2 (SI System):

1. The following conversion factors and approximations are being employed:

   1 cm/km^2 = 67.12 ML (million liters)

   Hence, 19.6 cm/km^2 annually = 19.6 × 67.12 = 1315.6 ML annually = **3.6 MLD**.

2. A stream flow of about 1.46 MLD/km^2 is a good average for the well-watered sections of North America. Not all of it can be adduced economically by storage.

   For 75% development (0.75 × 1.46 MLD/km^2), about half a year's supply must generally be stored.

   For a catchment area of 259 km^2, therefore

   Storage = 0.75(1.46 MLD/km^2)(259 km^2)(0.5 × 365) = 51,758 ML = **51.758 BL** (billion liters).

   In semiarid regions storage of three times the mean annual stream flow is not uncommon, that is, water is held over from wet years to supply demands during dry years.

3. For an average consumption of 567.8 Lpcd, the drainage area of 259 km^2 and impoundage of 51.758 BL will supply a population of

   (0.75 × 1.46 MLD/km^2)(259 km^2)(1,000,000 L/ML)/(567.8 Lpcd) = **500,000 persons**.

4. For water supply by continuous draft, low water flows rather than average annual yields govern. In well-watered sections of North America these approximate 28.32 L/s or 0.094316 MLD/km^2.

   A catchment area of 259 km^2, therefore, can supply without storage

   (259 km^2)(0.094316 MLD/km^2)(1,000,000 L/ML)/(567.8 Lpcd) = **43,000 people**.

   This is compared against 500,000 people in the presence of proper storage.