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

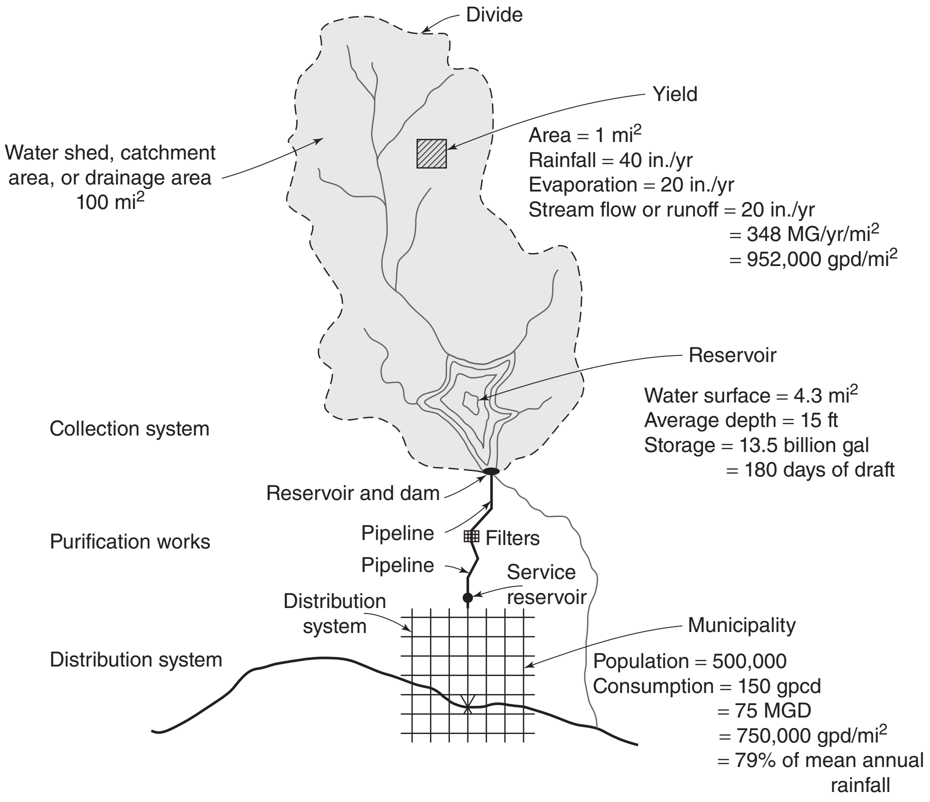


Figure 1.1 Rainfall, runoff, storage, and draft relations in the development of surface water (conversion factors: 1 $\text{mi}^2 = 2.59\ \text{km}^2$; 1 in./yr = 25.4 mm/yr; 1 ft = 0.3048 m; 1 $\text{MG/yr/mi}^2 = 1.46\ \text{ML/yr/km}^2$; 1 $\text{gpd/mi}^2 = 1.461\ \text{L/d/km}^2$; 1 billion gal = 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):

$$\text{Gross yield} = 3{,}000\ \text{ft}^2 \times (15/12\ \text{ft}) \times 7.48\ \text{gal/ft}^3 = 28{,}100\ \text{gal annually} = 28{,}100\ \text{gal}/365\ \text{days} = 77\ \text{gpd}.$$

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):

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

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

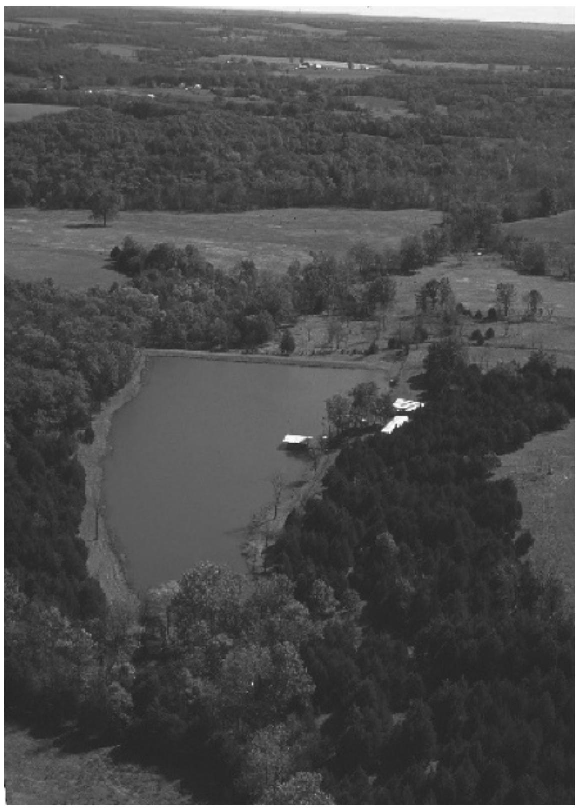


Figure 1.2 A watershed lake in Western Missouri provides water supply (Courtesy of the National Resources Conservation Service and USDA).

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 $= 20\ \text{in.}/\text{km}^2$ annually $= 19.6\ \text{cm}/\text{km}^2$, (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 ($0.75 \times 1\ \text{MGD}/\text{km}^2$ or $0.75 \times 1.46\ \text{MLD}/\text{km}^2$), 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.

The maximum yield of groundwater is directly proportional to the size of the intake area and to the difference between precipitation and the sum of evapotranspiration and storm runoff. Laterally, flow extends across the width of the aquifer; vertically, it is as deep as the zone of open pores and passages in Earth's crust and as shallow as the *groundwater table*. When the water surface rises and falls with seasonal changes in recharge, flow is unconfined or free, and the groundwater table slopes downward more or less parallel to the ground surface. Flow then moves at right angles to the water table contours. If a porous stratum dips beneath an impervious layer, flow is confined as in a pipe dropping below the hydraulic grade line. When this kind of aquifer is tapped, *artesian water* rises from it under pressure, in some geological situations, even in free-flowing fountains. In other geological formations, water is perched on a lens of impervious material above the true groundwater table.

Groundwater reaches daylight through springs when (a) the ground surface drops sharply below the normal groundwater table (depression springs); (b) a geological obstruction impounds soil water behind it and forces it to the surface (contact springs); and (c) a fault in an impervious stratum lets artesian water escape from confinement (also contact springs). A cutoff wall carried to bedrock will hold back subsurface as well as surface flows behind an impounding dam and so put the full capacity of the catchment area to use unless there is lateral leakage through the sides of the reservoir or around the abutments of the dam.

The rate of flow through the substantially vertical cross-section of ground at right angles to the direction of flow is not great. Because of the high resistance of the normally narrow pores of the soil, the water moves forward only slowly, traveling about as far in a year as stream flow does in an hour. Natural rates of flow are seldom more than a few feet per hour (or meters per hour); nor are they less than a few feet per day (or meters per day) in aquifers delivering useful water supplies. However, if a well is sunk into the ground and the level of water in it is lowered by pumping, water is discharged into the well not only from the direction of natural flow but from all directions. That is why wells can be spaced many times their own diameter apart and yet intercept most of the water escaping through the intervening space.

1.6.1 Springs

Springs are usually developed to capture the natural flow of an aquifer. In favorable circumstances their yield can be increased by driving collecting pipes or galleries, more or less horizontally, into the water-bearing formations that feed them. Pollution generally originates close to the point of capture. It is prevented by (a) excluding shallow seepage waters through encircling the spring with a watertight chamber penetrating a safe distance into the aquifer and (b) diverting surface runoff away from the immediate vicinity. Some springs yield less than 1 gpm (3.78 L/min); a few yield more than 50 MGD (189 MLD). Some are perennial; others are periodically or seasonally intermittent.

Figure 1.3 A well provides about 1.5 MGD (5.68 MLD) of water to Central Maui, HI (Courtesy of the Department of Water Supply, Maui County, HI).

1.6.2 Wells

Depending on the geological formations through which they pass and on their depth, wells are *dug*, *driven*, *bored*, or *drilled* into the ground. A well and its pumping equipment are shown in Fig. 1.3. Dug and driven wells are usually confined to soft ground, sand, and gravel at depths normally less than 100 ft (30 m). Hard ground and rock generally call for bored and drilled wells sunk to depths of hundreds and even thousands of feet. In well-watered regions successful wells of moderate depth and diameter yield 1–50 gpm (4–190 L/min) in hard rock and 50–500 gpm (190–1900 L/min) in coarse sand and gravel as well as coarse sandstone. Wells in deep aquifers may yield 100 gpm (400 L/min) or more.

Except in hard rock, particularly limestone, without sand or gravel cover, wells are generally not polluted by lateral seepage but by vertical entrance of pollution at or near the ground surface. Pollution is excluded by watertight casings or seals extending into the aquifer and at least 10 ft (3 m) below the ground surface, together with diversion of surface runoff from the well area and its protection against inundation by nearby streams.

1.6.3 Infiltration Galleries

Groundwater traveling toward streams or lakes from neighboring uplands can be intercepted by infiltration galleries laid more or less at right angles to the direction of flow and carrying entrant water to pumping stations. Water is drawn into more or less horizontal conduits from both sides, or the riverside is blanked off to exclude the often less satisfactory water seeping in from the river itself. Infiltration basins

EXAMPLE 1.3 DETERMINATION OF AQUIFER YIELD

Make a rough estimate of the yield of an aquifer 20 ft (6.10 m) deep through which water moves at a rate of 3 ft (0.91 m) a day (1) if all of the groundwater laterally within 500 ft (152 m) of the well comes fully within its influence and (2) if a gallery 1,000 ft (305 m) long collects water from both sides.

Solution 1 (US Customary System):

1. $20\ \text{ft} \times 500\ \text{ft} \times 2 \times 3\ \text{ft/d} \times (7.5\ \text{gal/ft}^3)/(1{,}440\ \text{min/d}) = \mathbf{310\ gpm}$.
2. $20\ \text{ft} \times 1{,}000\ \text{ft} \times 2 \times 3\ \text{ft/d} \times (7.5\ \text{gal/ft}^3)/(1{,}000{,}000) = \mathbf{0.90\ MGD}$.

Solution 2 (SI System):

1. $(6.10\ \text{m})(305\ \text{m})(0.91\ \text{m})(1{,}000\ \text{L/m}^3)(1/1{,}440\ \text{min}) = 1176\ \text{L/min}$.
2. $2(6.10\ \text{m})(305\ \text{m})(0.91\ \text{m})/\text{d} = 3{,}397\ \text{m}^3/\text{d} = 3{,}396{,}500\ \text{L/d} = \mathbf{3.4\ MLD}$.

and trenches are similar in conception. They are, in essence, large, or long, shallow, open wells. Filter cribs built into alluvial deposits of streams intercept the underflow. Groundwater can also be collected from the driftways and slopes of mines, galleries driven into mountainsides specifically for this purpose, or abandoned mines. Some infiltration galleries yield as much as 1 MGD/1,000 ft (12.4 MLD/1,000 m) of gallery. They are particularly useful in tapping aquifers of shallow depth or where deep saline waters are to be excluded.

1.6.4 Recharging Devices

As outlined earlier, the yield of groundwater works can be augmented or maintained at high level by water spreading or diffusion. The necessary structures are built close to the collecting works within the groundwater shed. Charging ditches or basins are filled with river or lake water by gravity or pumping. In the flooding method, water diverted from streams by check dams is led onto a suitable area of pervious soils. The applied waters soak into the ground and increase its natural flows. The incentive is either augmentation of a dwindling or inadequate supply or taking advantage of natural filtration as a means of water purification. Gathering a more uniformly cool water is also a consideration. Badly polluted surface water may be partially purified before it is introduced into the charging structure. Some diffusion galleries and wells return waters abstracted earlier from the ground for cooling and other purposes.

Groundwater collection works usually include pumps. To them water flows from all or much of the well field either by gravity through deep-lying conduits or under negative pressure through suction mains. Individual pumping units are often used instead, especially when the water table lies at considerable depths.

Most natural groundwaters are clean, palatable, and cool. However, passage through some soils may make them unpalatable, unattractive, corrosive, or hard (soap consuming). Their treatment must be varied according to needs.

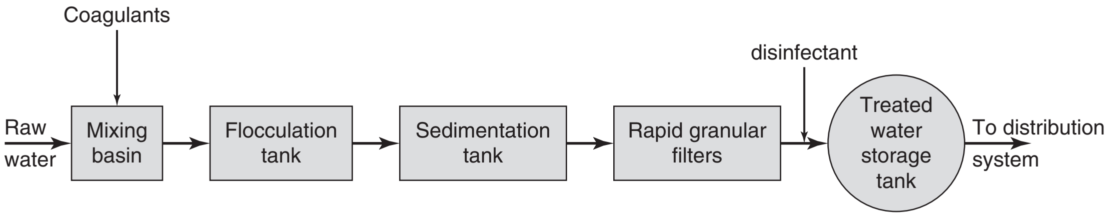
To determine the yield of groundwater areas, the engineer must know the geology as well as the hydrology of the region. He can learn much from existing supplies in nearby areas, but his ultimate judgment must generally rest on the behavior of test wells.

1.7 PURIFICATION WORKS

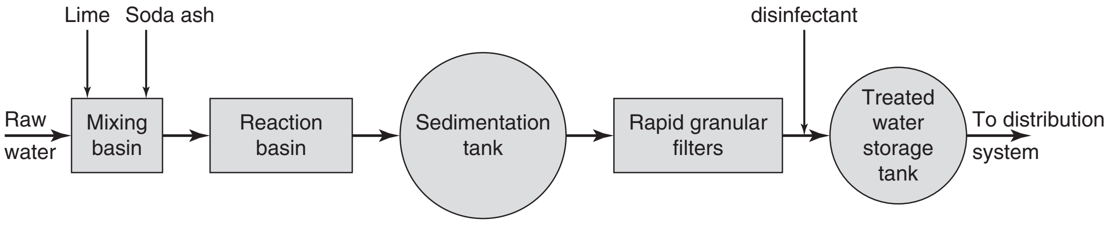
The quality of some waters from surface or ground sources is naturally satisfactory for all common uses. *Disinfection* may be the only required safeguard. Other waters contain objectionable substances that must be removed, reduced to tolerable limits, destroyed, or otherwise altered in character before the water is sent to the consumer. Impurities are acquired in the passage of water through the atmosphere, over the earth's surface, or through the pores of the earth. Their pollution is associated with man's activities, in particular, with his own use of water in household and industry and the return of spent water to natural water courses. Some of the *heavy metals* (lead, copper, zinc, and iron) come from the corrosion of metallic water pipes. Contamination of distribution systems through cross-connections with impure water supplies and through *backflow* in plumbing systems is another hazard. (Backflow permits water drawn into a fixture, tank, or similar device to flow back into the supply line by gravity or by siphonage.)

How to treat a given supply depends on its inherent traits and on accepted water quality standards. Municipal works must deliver water that is (a) hygienically safe, (b) aesthetically attractive and palatable, and (c) economically satisfactory for its intended uses. The most common classes of municipal water purification works and their principal functions are as follows:

1. *Filtration plants* remove objectionable color, turbidity, and bacteria as well as other potentially harmful organisms by filtration through sand or other granular substances after necessary preparation of the water by coagulation and sedimentation (Fig. 1.4a).



(*a*) Surface water filtration plant



(*b*) Groundwater softening plant

Figure 1.4 Common types of water treatment plants. (Note: A sedimentation tank may be replaced by a dissolved air flotation tank.)

2. *Iron and manganese treatment plants* remove excessive amounts of iron and manganese by oxidizing the dissolved metals and converting them into insoluble flocs removable by sedimentation and filtration.
3. *Softening plants* remove excessive amounts of scale-forming, soap-consuming ingredients, chiefly calcium and magnesium ions (a) by the addition of lime and soda ash, which precipitate calcium as a carbonate and magnesium as a hydrate (Fig. 1.4b) or (b) by passage of the water through cation exchange media that substitute sodium for calcium and magnesium ions and are themselves regenerated by brine.

Today most water supplies are either chlorinated or ozonated to ensure their disinfection. Lime or other chemicals are often added to reduce the corrosiveness of water to iron and other metals and so to preserve water quality during distribution and ensure a longer life for metallic pipes in particular. Odor- or taste-producing substances are adsorbed onto activated carbon or destroyed by high doses of chlorine, chlorine dioxide, or other oxidants. Numerous other treatment methods serve special needs. The perspective of a water treatment plant in northern Portugal is shown in Fig. 1.5.

Water purification plants must take into consideration these design functions:

1. *Process design:* An understanding of unit operations that bring about the removal or modification of objectionable substances.
2. *Hydraulic design:* A knowledge of how water flows through the structures composing water purification plants: channels, pipes including perforated pipes, gates, measuring devices, basins, beds of sand and other granular materials, and pumps.
3. *Structural design:* A comprehension of the behavior of needed structures under load.
4. *Economic design:* An appreciation of treatment costs and associated benefits.

The following normally applicable requirements provide the reader with a concept of the sizing of principal structures:

1. *Mixing basins* hold a few minutes of flow.
2. *Flocculating and reaction basins* hold about half an hour's flow.
3. *Sedimentation basins* hold an hour or more of flow and are rated at about 0.50 gpm/ft^2 (20 L/min/m^2) of water surface area.

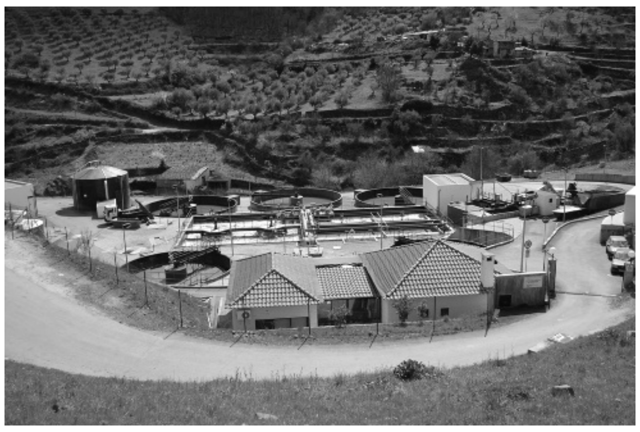


Figure 1.5 Water treatment plant in Braganca, Portugal (*Source:* http://en.wikipedia.org/wiki/Image:Bragan%C3%A7a43.jpg).

EXAMPLE 1.4 DETERMINATION OF THE CAPACITY OF TREATMENT PLANT UNITS

Estimate the capacity of the components of a rapid sand filtration plant (Fig. 1.5) that is to deliver 10 MGD or 6,940 gpm (37.85 MLD or 26,268 L/min) of water to a city of 67,000 people.

Solution 1 (US Customary System):

1. Two mixing basins, $H = 10$ ft deep; number of mixing basins $N = 2$.
   (a) Assumed detention period $t = 2$ min.
   (b) Volume $V = Qt/N = 6{,}940 \times 2/2 = 6{,}940$ gal $= 928$ ft^3 each.
   (c) Surface area $A = V/H = 928/10 = 92.8$ ft$^2 = 0.785\ D^2$.
   (d) Diameter $D = \sqrt{\dfrac{A \times 4}{\pi}} = \sqrt{\dfrac{92.8 \times 4}{\pi}} =$ **10.9 ft**.
2. Two flocculating basins, $H = 10$ ft deep.
   (a) Assumed detention period $t = 30$ min; number of flocculating basins $N = 2$.
   (b) Volume $V = Qt/N = 6{,}940 \times 30/2 = 104{,}000$ gal $= 13{,}900$ ft^3.
   (c) Surface area $A = V/H = (13{,}900\ \text{ft}^3)/(10\ \text{ft}) =$ **1,390 ft^2** each (such as 20 ft by 70 ft).
3. Two settling basins, $H = 10$ ft deep, but allow for 2 ft of sludge; number of settling basins $N = 2$.
   (a) Assumed detention period $t = 2$ h.
   (b) Effective volume $V = Qt/N = 6{,}940 \times 2 \times 60/2 = 416{,}000$ gal $= 55{,}700$ ft^3.
   (c) Surface area $A = V/H = 55{,}700/(10 - 2)$ ft $=$ **6,960 ft^2** (such as 35 ft by 200 ft).
   (d) Surface rating $\text{SR} = Q/A = 6{,}940/6{,}960 = 1.0\ \text{gpm/ft}^2$.
4. Six rapid sand filters.
   (a) Assumed surface rating $\text{SR} = Q/A = 3\ \text{gpm/ft}^2$; number of filters $N = 6$.
   (b) Area $A = Q/(N \times \text{SR}) = 6{,}940/(6 \times 3) =$ **385 ft^2** (such as 15 ft by 26 ft).

Solution 2 (SI System):

1. Two mixing basins, $H = 3.05$ m deep; number of mixing basins $N = 2$.
   (a) Assumed detention period $t = 2$ min.
   (b) Volume $V = Qt/N = (26{,}268 \times 2)/2 = 26{,}268$ L $= 26.27$ m^3 each.
   (c) Surface area $A = V/H = (26.27/3.048) = 8.62$ m^2.
   (d) Diameter $D = \sqrt{\dfrac{A \times 4}{\pi}} = \sqrt{\dfrac{8.62 \times 4}{\pi}} =$ **3.31 m**.
2. Two flocculating basins, $H = 3.05$ m deep.
   (a) Assumed detention period $t = 30$ min; number of flocculating basins $N = 2$.
   (b) Volume $V = Qt/N = (26{,}268\ \text{L/min} \times 30\ \text{min})/2 = 394{,}020\ \text{L} = 394\ \text{m}^3$.
   (c) Surface area $A = V/H = (394\ \text{m}^3)/(3.05\ \text{m}) =$ **129.27 m^2** each (such as **6.1 m × 21.3 m**).
3. Two settling basins, $H = 3.05$ m deep, but allow for 0.61 m of sludge; number of settling basins $N = 2$.
   (a) Assumed detention period $t = 2$ h.
   (b) Effective volume $V = Qt/N = (26{,}268\ \text{L/min} \times 2 \times 60\ \text{min})/2 = 1{,}576{,}080\ \text{L} = 1{,}576\ \text{m}^3$.
   (c) Surface area $A = V/H = (1{,}576\ \text{m}^3)/(3.05\ \text{m} - 0.61\ \text{m}) =$ **646 m^2** (such as 10.7 m by 61 m).
   (d) Surface rating $\text{SR} = Q/A = (26{,}268\ \text{L/min})/(646\ \text{m}^2) = 40.7\ \text{L/min/m}^2$.
4. Six rapid sand filters.
   (a) Assumed surface rating $\text{SR} = Q/A = 122.1\ \text{L/min/m}^2$; number of filters $N = 6$.
   (b) Area $A = Q/(N \times \text{SR}) = (26{,}268\ \text{L/min})/(6 \times 122.1) =$ **35.86 m^2** (such as 4.6 m by 7.9 m).

4. *Slow sand filters* pass water at rates of about 3 MGD/acre (28 MLD/ha) in surface water filtration, stepping up to about 10 MGD/acre (94 MLD/ha) in groundwater treatment for iron and manganese removal or when they are preceded by roughing filters.
5. *Rapid filters* operate at rates of 125 MGD/acre or 2 gpm/ft^2 (1170 MLD/ha or 81 L/min/m^2), but rates run higher in modern works that include flocculating chambers.
6. *Coke tricklers* for aeration are rated at about 75 MGD/acre or 1.2 gpm/ft^2 (700 MLD/ ha or 50 L/min/m^2).

1.8 TRANSMISSION WORKS

Supply conduits, or aqueducts, transport water from the source of supply to the community and so form the connecting link between collection works and distribution systems. Source location determines whether conduits are short or long and whether transport is by gravity or pumping. Depending on topography and available materials, conduits are designed for open-channel or pressure flow. They may follow the hydraulic grade line as canals dug through the ground, flumes elevated above the ground, grade aqueducts laid in balanced cut and cover at the ground surface, and grade tunnels penetrating hills; or they may depart from the hydraulic grade line as pressure aqueducts laid in balanced cut and cover at the ground surface, pressure tunnels dipping beneath valleys or hills, and pipelines of fabricated materials following the ground surface, if necessary over hill and through dale, sometimes even rising above the hydraulic grade line. The 336 mi (541 km) long Central Arizona Project aqueduct shown in Fig. 1.6 is the largest and most expensive aqueduct system ever constructed in the United States. The Colorado River aqueduct of the Metropolitan Water District of Southern California is 242 mi (389 km) long and includes 92 mi (148 km) of grade tunnel, 63 mi (101 km) of canal, 54 mi (87 km) of grade aqueduct, 29 mi (47 km) of inverted siphons, and 4 mi (6.4 km) of force main. The Delaware aqueduct of New York City comprises 85 mi (137 km) of pressure tunnel in three sections. Pressure tunnels 25 mi (40 km) in length supply the metropolitan districts of Boston and San Francisco. The supply conduits of Springfield, MA, are made of steel pipe and reinforced concrete pipe and those of Albany, NY, of cast-iron pipe (CIP).

The size and shape of supply conduits are determined by hydraulic, structural, and economic considerations. Velocities of flow ordinarily lie between 3 and 5 ft/s (0.91 and 1.52 m/s). Requisite capacities depend on the inclusion and size of supporting *service* or *distributing reservoirs*. If these store enough water to (a) care for hourly variations in water consumption in excess of inflow, (b) deliver water needed to fight serious fires, and (c) permit incoming lines to be shut down for inspection and minor repairs, the supply conduits need operate only at the maximum daily rate, about 50% in excess of the average daily rate. Ordinarily, required storage approximates a day's consumption. Distribution reservoirs are open or covered basins in balanced cut and fill, standpipes, or elevated tanks. Selection depends on size and location in particular reference to available elevations above the area served (Fig. 1.7). More than one reservoir may be needed in large systems. Open reservoirs are troubled by soot and dust falls, by algal growths, and in seacoast cities by sea gulls. Today, covered reservoirs are preferred.

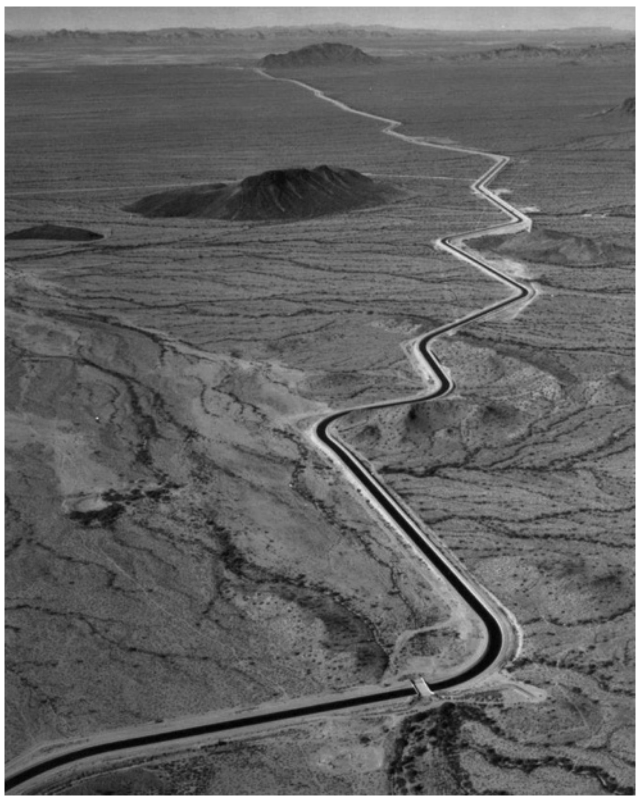
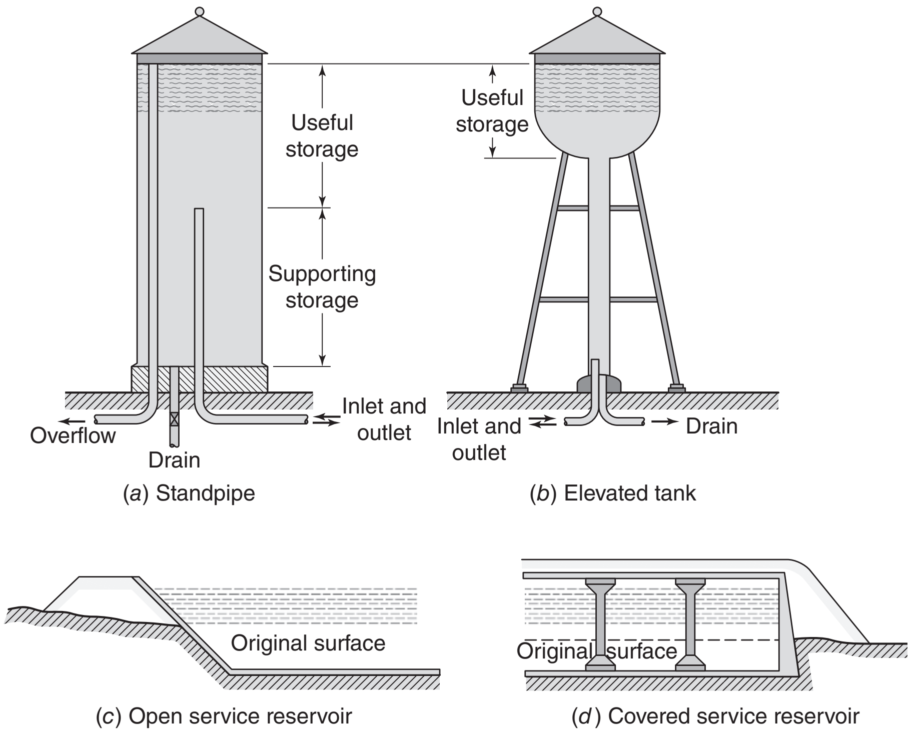


Figure 1.6 Central Arizona Project aqueduct (*Source:* http://en.wikipedia.org/wiki/Image:Arizona_cap_canal.jpg).

1.9 DISTRIBUTION WORKS

Supply conduits (Fig. 1.8) feed their waters into the distribution system that eventually serves each individual property—household, mercantile establishment, public building, or factory (Fig. 1.1). Street plan, topography, and location of supply works and service storage establish the type of distribution system and its character of flow. In accord with the street plan, two distribution patterns emerge: (a) a *branching pattern* on the outskirts of the community, in which ribbon development follows the primary arteries of roads and streets (Fig. 1.9a), and (b) a *gridiron pattern* within the built-up portions of the community where streets crisscross and water mains are interconnected (Fig. 1.9).



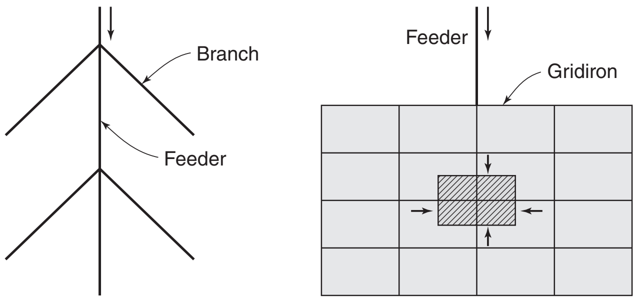
(*a*) Standpipe (*b*) Elevated tank

(*c*) Open service reservoir (*d*) Covered service reservoir

Figure 1.7 Four types of service, or distribution, reservoirs.

Hydraulically, the gridiron system has the advantage of delivering water to any spot from more than one direction and of avoiding dead ends. Gridiron systems are strengthened by substituting for a central feeder a loop or belt of feeders that supplies water to the *congested*, or *high-value*, district from at least two directions. This more or less doubles the delivery of the grid. In large systems feeders are constructed as pressure tunnels, pressure aqueducts, steel pipes, or reinforced concrete pipes. In smaller communities the entire distribution system may consist of CIPs. Cast iron is, indeed, the most common material for water mains, but asbestos-cement, in general, and plastics, in the case of small supplies, are also important.

Figure 1.8 A pipeline in the Goldfields Water Supply Scheme, Perth, Australia (*Source:* http://en.wikipedia.org/wiki/Image:Goldfields_Pipeline_SMC.JPG).



(*a*) Branching pattern with dead ends (*b*) Gridiron pattern with looped feeder

High value district is crosshatched

Figure 1.9 Patterns of water distribution systems.

EXAMPLE 1.5 ESTIMATION OF THE SIZE OF A WATER CONDUIT

Estimate roughly the size of a supply conduit leading to an adequate distributing reservoir serving (i) relatively small residential community of 10,000 people and (ii) a relatively large industrial community of 400,000 people.

The following are the design conditions specifically for a North American region:

a. The average daily water consumption for small communities with populations of 10,000 or less = 100 gpcd (378.5 Lpcd).

b. Average daily water consumption for communities with populations of greater than 10,000 = 150 gpcd (567.8 Lpcd).

c. Maximum daily water consumption is about 50% greater than average daily water consumption.

d. The design water velocity in the circular conduit when flowing full = 4 ft/s = 1.22 m/s.

Solution 1 (US Customary System):

1. Average daily water consumption at (a) 100 gpcd and (b) 150 gpcd for the 10,000 people community and the 400,000 people community, respectively:
   (i) $10{,}000 \times 100/1{,}000{,}000 = \mathbf{1.0\ MGD}$.
   (ii) $400{,}000 \times 150/1{,}000{,}000 = \mathbf{60\ MGD}$.
2. Maximum daily water consumption is 50% greater than the average:
   (i) $1.0 \times 1.5 = 1.5\ \text{MGD} = 1.5 \times 1{,}000{,}000/(7.5 \times 24 \times 60 \times 60) = \mathbf{2.32\ ft^3/s}$.
   (ii) $60 \times 1.5 = 90\ \text{MGD} = 90 \times 1{,}000{,}000/(7.5 \times 24 \times 60 \times 60) = \mathbf{139\ ft^3/s}$.
3. Diameter of circular conduit flowing at 4 ft/s:
   (i) Cross-sectional area $A = Q/v = 2.32/4 = \pi\ D^2/4 = 0.785\ D^2$.
   Diameter $D = 0.833$ ft = 10 in. for the small 10,000 people community.
   (ii) Cross-sectional area $A = Q/v = 139/4 = \pi\ D^2/4 = 0.785\ D^2$.
   Diameter $D = 6.667$ ft = **80 in**. for the large 400,000 people community.

Solution 2 (SI System):

1. Average daily water consumption = 378.5 Lpcd for the 10,000 people community and average daily water consumption = 567.8 Lpcd for the 400,000 people community.
   (i) $10{,}000 \times 378.5/1{,}000{,}000 = \mathbf{3.785\ MLD}$.
   (ii) $400{,}000 \times 567.8/1{,}000{,}000 = \mathbf{227.1\ MLD}$.
2. Maximum daily water consumption is 50% greater than the average:
   (i) $(3.785\ \text{MLD}) \times 1.5 = 5.6775\ \text{MLD} = 5677.5\ \text{m}^3/\text{d} = (5677.5\ \text{m}^3)/(1{,}440 \times 60)\ \text{s} = 0.066\ \text{m}^3/\text{s} = \mathbf{66\ L/s}$.
   (ii) $(227.1\ \text{MLD}) \times 1.5 = 340.65\ \text{MLD} = 340{,}650\ \text{m}^3/\text{d} = (340{,}650\ \text{m}^3)/(1{,}440 \times 60)\text{s} = \mathbf{3.94\ m^3/s}$.
3. Diameter of circular conduit flowing at 1.22 m/s:
   (i) Cross-sectional area $A = Q/v = (0.066\ \text{m}^3/\text{s})/(1.22\ \text{m/s}) = 0.054\ \text{m}^2 = 0.785\ D^2$.
   Diameter $D = 0.26$ m = 260 mm for the small 10,000 people community.
   (ii) Cross-sectional area $A = Q/v = (3.94\ \text{m}^3/\text{s})/(1.22\ \text{m/s}) = 3.23\ \text{m}^2 = 0.785\ D^2$.
   Diameter $D = 2.03$ m = **2,030 mm** for the large 400,000 people community.

1.9.1 High and Low Services

Sections of the community too high to be supplied directly from the principal, or *low-service*, works are generally incorporated into separate distribution systems with independent piping and service storage. The resulting *high services* are normally fed by pumps that take water from the main supply and boost its pressure as required. Areas varying widely in elevation may be formed into intermediate districts or zones. Gated connections between the different systems are opened by hand during emergencies or go into operation automatically by means of pressure-regulating valves.

1.9.2 Fire Supplies

Before the days of high-capacity, high-pressure, motorized fire engines, conflagrations in the congested central, or *high-value*, district of some large cities were fought through independent high-pressure systems of pipes and hydrants. Taking water from the public supply and boosting its pressure by pumps in power stations whenever an alarm was rung in, these systems performed well. For extreme emergencies, rigorously protected connections usually led to independent sources of water: rivers, lakes, or tidal estuaries. Large industrial establishments, with heavy investments in plant, equipment, raw materials, and finished products, concentrated in

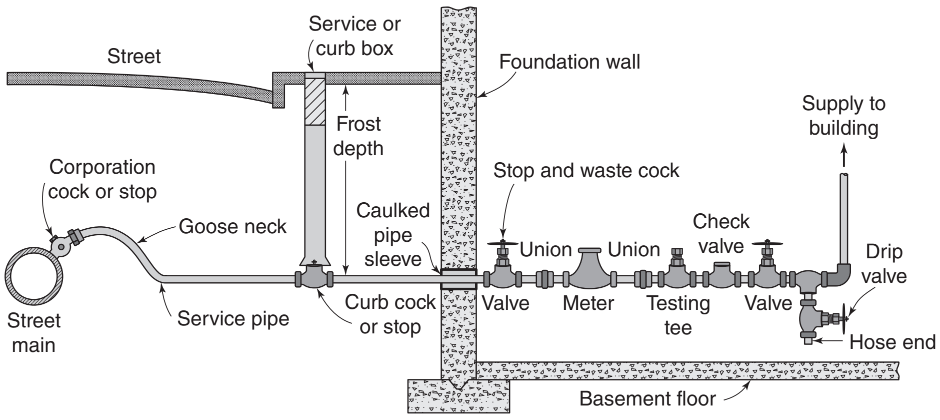


Figure 1.10 Service pipe, fittings, and accessories. There are many possible modifications, both inside and outside the building. In many instances, the meter is conveniently placed in a vault outside the building.

a small area, are generally equipped with high-pressure fire supplies and distribution networks of their own. Because such supplies may be drawn from sources of questionable quality, some regulatory agencies enforce rigid separation of private fire supplies and public systems. Others prescribe protected cross-connections that are regularly inspected for tightness. Ground-level storage and pumping are less advantageous.

1.9.3 Pressures

In normal municipal practice, pressures of 60–75 psig (416–520 kPa) are maintained in business blocks and 40 psig (278 kPa) in residential areas. Higher pressures, such as 100 psig (694 kPa) or more, delivering adequate amounts of water for firefighting through hoses attached directly to fire *hydrants* are no longer important. Instead, modern motor pumpers can discharge thousands of gallons per minute at even greater pressures. Moreover, low operating pressures make for low *leakage* from mains and reduce the amount of water that is *unaccounted* for. To supply their upper stories, tall buildings boost water to tanks at various elevations and on their roofs or in towers. In individual industrial complexes, the water pressure may be raised during fires by fixed installations of fire pumps.

1.9.4 Capacity

The capacity of distribution systems is dictated by domestic, industrial, and other normal water uses and by the *standby* or *ready-to-serve* requirements for firefighting. Pipes should be able to carry the maximum *coincident* draft at velocities that do not produce high pressure drops and water hammer. Velocities of 2–4 ft/s (0.60–1.2 m/s) and minimum pipe diameters of 6 in. (150 mm) are common in North American municipalities.

1.9.5 Service to Premises

Water reaches individual premises from the street main through one or more service pipes tapping the distribution system. The building supply between the public main and the take-offs to the various plumbing fixtures or other points of water use is illustrated in Fig. 1.10. Small services are made of cement-lined iron or steel, brass of varying copper content, admiralty metal, copper, and plastics such as polyethylene (PE), high-density polyethylene (HDPE), or polyvinyl chloride (PVC). Because lead and lead-lined pipes may corrode and release lead to the water, they are no longer installed afresh. For large services, coated or lined CIP is often employed. For dwellings and similar buildings, the minimum desirable size of service is $^{3}/_{4}$ in. (19 mm). *Pipe-tapping machines* connect services to the main without shutting off the water. They also make larger connections within water distribution systems.

1.10 WATER SYSTEMS MANAGEMENT

Construction of water supplies from the ground up, or their improvement and extension, progresses from preliminary investigations or planning through financing, design, and construction to operation, maintenance, and repair. Political and financial procedures are involved as well as engineering.

1.10.1 Municipal Supplies

The cost of public water supplies in the United States provides the reader with some concept of the magnitude of engineering activity and responsibility associated with their design and construction. Per capita investment in physical plant depends on many factors: nature, proximity, and abundance of suitable water sources; need for water treatment; availability and price of labor and materials; size and construction conditions of the system; habits of the people; and characteristics of the areas served. Wide differences in these factors make for much variation in initial costs. For communities in excess of 10,000 population, replacement costs in North America lie in the vicinity of $1,500 per capita (for 2008 price levels; for other years multiply by the ratio of an applicable *utilities price index*; see Appendix 16), with much of the investment in small communities chargeable to fire protection.

EXAMPLE 1.6 ESTIMATION OF WATERWORKS COST

Roughly, what is the replacement cost of a conventional filtration plant and other waterworks for a city of 100,000 people and what is the average plant flow?

The following conditions are assumed:

a. A per capita first cost of $1,500 in 2008.

b. Thirty percent of the first cost is to be invested in the collection works, 10% in the purification works, and 60% in the distribution works.

c. A water consumption rate of 150 gpcd (568 Lpcd) for the city.

Solution 1 (US Customary System):

1. Assuming a per capita cost of $1,500, the total first cost is 1,500 × 100,000 = **$150,000,000**.
2. Assuming that 30% of this amount is invested in the collection works, 10% in the purification works, and 60% in the distribution works, the breakdown is as follows:
    - Collection works 0.3 × 150,000,000 = **$45,000,000**.
    - Purification works 0.10 × 150,000,000 = **$15,000,000**.
    - Distribution works 0.60 × 150,000,000 = **$90,000,000**.
3. Assuming a water consumption rate of 150 gpcd, the total water consumption of the city is 150 × 100,000 gpd = **15 MGD**.

Solution 2 (SI System):

1. $1,500 × 100,000 = **$150,000,000**.
2. Same as Solution 1.
    - Collection works 0.3 × 150,000,000 = **$45,000,000**.
    - Purification works 0.1 × 150,000,000 = **$15,000,000**.
    - Distribution works 0.6 × 150,000,000 = **$75,000,000**.
3. Assuming a water consumption of 568 Lpcd, the total water consumption of the city is 568 × 100,000 Lpd = **56.8 MLD**.

Of the various system components, collection and transportation works cost about a fourth, distribution works slightly less than a half, purification and pumping works about a tenth, and service lines and meters nearly a sixth of the total. The initial cost of conventional water filtration plants is about $1,500,000 per MGD ($396,000 per MLD) capacity, varying with plant size as the two-thirds power of the capacity. The cost of water treatment, excluding fixed charges, lies in the vicinity of $420 per MG ($111 per ML), varying with plant output capacity inversely as the two-fifths power of the daily production. Including interest and depreciation as well as charges against operation and maintenance, water costs $300 to $3,000 per million gallons ($80 to $800 per million liters) and is charged for accordingly. As one of our most prized commodities, water is nevertheless remarkably cheap—as low as 12 cents a ton delivered to the premises of large consumers and as little as 24 cents a ton to the taps of small consumers.

1.10.2 Individual Small Supplies

The term *individual* describes those situations in which the needs and amenities of water supply and wastewater disposal are normally satisfied by relatively small and compact systems individually owned, developed, operated, and kept within the property lines of the owner. Normally, this implies construction of wanted or required systems through individual rather than community effort. But there have been developments for villages and communities with scattered buildings in which local government has taken the initiative and assumed responsibility for construction and care of individualized systems. Property owners, as well as the community, then enjoy the benefits of adequate planning, design, construction, management, and supervision. Otherwise, unfortunately, necessary works are rarely designed by qualified engineers and often end up not satisfying their purposes, both in a sanitary and an economic sense.

Reasonably good results can be obtained if (a) engineering departments of central health authorities publish manuals of design, construction, and operation that fit local conditions and (b) they give needed advice and supervision as well as provide for regulation. Nevertheless, villages and fringe areas are best served, in the long run, by the extension of central water lines and sewers or by incorporation of *water* and *sewer districts* comprising more than a single unit of local government.

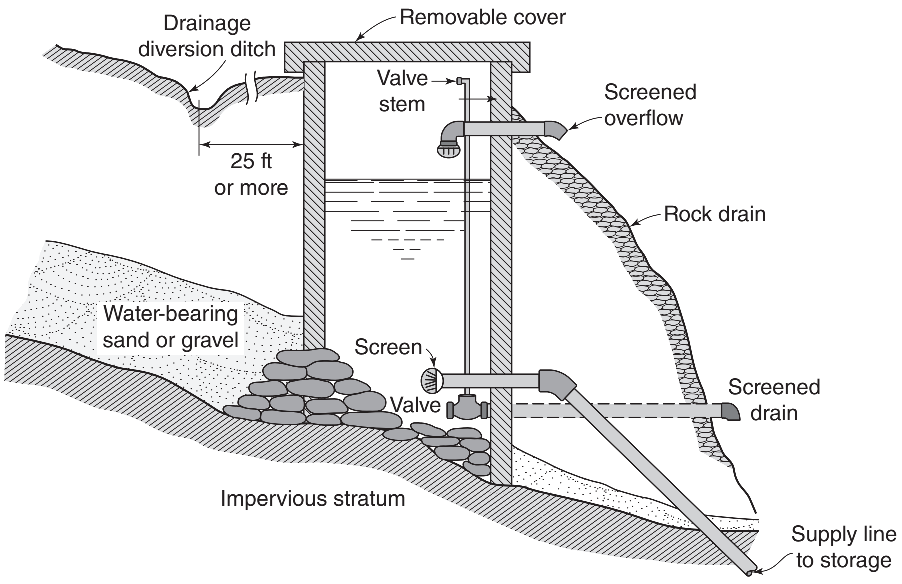


Figure 1.11 Water supply from spring (After US Public Health Service). Conversion factor: 1 ft = 0.3048 m.

1.11 INDIVIDUAL WATER SYSTEMS

Because of the natural purifying capacity and protection of the soil, individual and *rural* water supplies are generally drawn from springs, infiltration galleries, and wells. Where groundwater is highly mineralized or unavailable, rainwater is next best in general safety and quality. Only in uninhabited and well-protected upland areas should ponds and streams be tapped without purifying the waters drawn.

Some of the safeguards for groundwater works are illustrated in Figs. 1.11, 1.12, and 1.13. They share the following features in common:

1. **1.** Diversion of surface water from intake structures
2. **2.** Drainage of overflow or spillage waters away from intake structures
3. **3.** Water tightness of intake works for at least l0 ft (3 m) below the ground surface and, if necessary, until the aquifer is reached
4. **4.** Prevention of backflow into intakes; where there is no electric power, water is pumped by hand, wind, water, or gasoline engines

Individual and rural water supplies are not without their purification problems. Gravity and pressure filters are employed to improve waters of doubtful purity, and zeolite softeners and other ion-exchange units are used for the removal of unwanted hardness. Iron-bearing groundwaters that issue from their source sparklingly clear but become rusty on exposure to air (by oxidation and precipitation of iron) are best treated in manganese cation exchange units. Hexametaphosphates may keep iron from precipitating, but this requires skillful management. It may be advisable to seek an iron-free source instead.

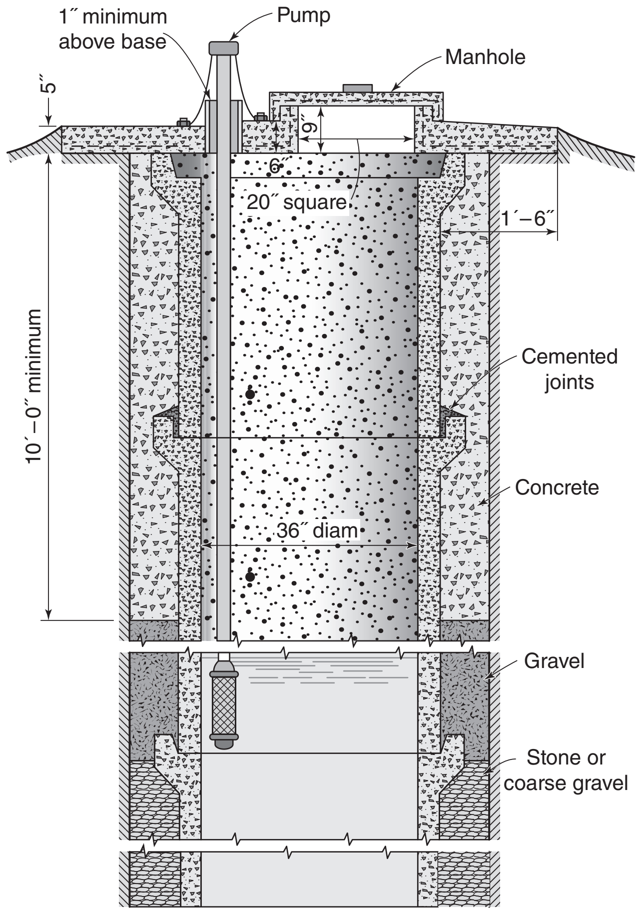


Figure 1.12 Water supply from dug well (After US Department of Agriculture). Conversion factors: 1′ = 1 ft = 0.3048 m; 1″ = 1 in. = 2.54 cm.

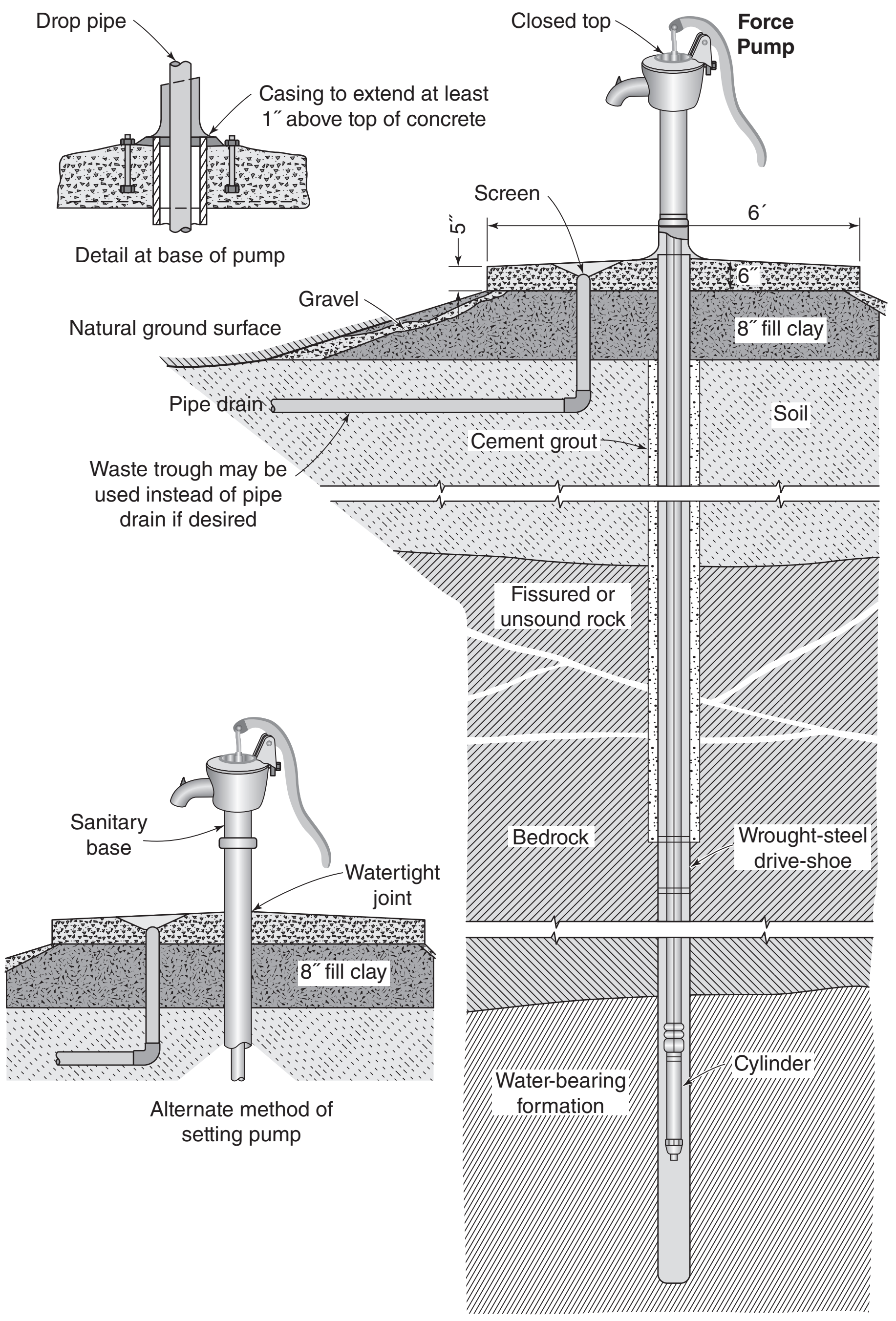


Figure 1.13 Water supply from driven well (After Virginia State Department of Health). Conversion factors: 1′ = 1 ft = 0.3048 m; 1″ = 1 in. = 2.54 cm.

Some soft groundwaters containing much carbon dioxide are highly corrosive. Passage through marble or limestone chips takes calcium into solution and reduces the carbon dioxide proportionately. Hardness is increased, but corrosiveness is decreased. For the chlorination of polluted rural supplies, there are solution-feed dosing devices that proportion the amount of added chlorine to flow. Instead, the householder may prefer to boil his drinking and culinary water. Investment in an inherently safe and satisfactory supply, however, is usually wisest in the long run.

PROBLEMS/QUESTIONS

1.1 What is the stream flow in MGD (MLD) for a catchment area of 80 mi^2 (207.2 km^2) where rainfall rate is 45 in./year (114.3 cm/year) and evaporation rate is 20 in./year (50.8 cm/year)?

1.2 A city is served by a raw water reservoir that has a water surface of 5.8 mi^2 (15.02 km^2) and an average effective depth of 18 ft (5.49 m). Determine the water storage volume.

1.3 The population of a city is 400,000, and the average daily per capita water demand is 150 gpcd (567.75 Lpcd). Determine the city's average daily water demand.

1.4 How many days of draft can a raw water reservoir support for a city of 400,000 people? The reservoir has a water surface of 5.8 mile^2 = 15.02 km^2 and an average effective depth of 18 ft = 5.49 m.

1.5 What percentage of mean annual runoff is to be consumed by a city of 400,000 people in an area with (a) rainfall rate = 45 in./year = 114.3 cm/year; (b) evaporation rate = 20 in./year = 50.8 cm/year; and (c) watershed catchment or drainage area = 80 mile^2 = 207.2 km^2?

1.6 Determine the net yield and water storage volume of a rainwater system assuming that (a) the net yield of a rain collection facility approximates two-thirds of its gross yield; (b) the mean annual rainfall = 25 in./year = 63.5 cm/year; (c) the mean annual evaporation rate is 8 in./year = 20.32 cm/year; (d) the rain collection roof area equals 3,200 ft^2 = 297.28 m^2; and (e) water storage volume equals 50% of annual net yield.

1.7 Determine the storage volume of a new raw water reservoir in accordance with the following given technical information: (a) city population = 400,000; (b) water consumption = 150 gpcd = 568 Lpcd; (c) watershed or catchment area = 80 mi^2 = 207.2 km^2; (d) rainfall rate = 45 in./year = 114.3 cm/year; (e) evaporation rate = 20 in./year = 50.8 cm/year; (f) minimum reservoir volume = 50% annual net yield or half of a year's water supply, whichever is greater; and (g) 75% water resources development.

1.8 Determine the number of people who can be sustainably supported by a watershed under the following conditions: (a) watershed area = 80 mi^2 = 207.2 km^2; (b) annual rainfall rate = 45 in./year = 114.3 cm/year; (c) annual evaporation rate = 20 in./year = 50.8 cm/year; (d) water resources development = 75%; (e) raw water reservoir volume to store 50% net annual yield or provide half of a year's water supply, whichever is higher = 13 BG = 49.205 BL; and (f) water consumption rate = 150 gpcd = 568 Lpcd.

1.9 Determine the number of people who can be adequately supported by a watershed under the following conditions: (a) watershed area = 80 mi^2 = 207.2 km^2; (b) water supply system with no reservoir for water storage; (c) low water flow = 0.1 ft^3/s = 64,600 gpd/mi^2 = 2.83 L/s = 0.00283 m^3/s; and (d) water consumption rate = 150 gpcd = 568 Lpcd.

1.10 Make a rough estimate of the groundwater movement velocity ($v = Q/A$) (ft/day or m/day) if (a) all of the groundwater laterally within 400 ft (122 m) of the well comes fully within its influence; and (b) the yield of the aquifer is 258 gpm (gallon per minute) = 976.53 L/min = 16.28 L/s; and the aquifer through which the groundwater moves is 25 ft (7.62 m) deep.

1.11 Estimate the surface area (ft^2, or m^2) of a slow sand filter that is to deliver water to a village of 1,000 people assuming that (a) the average daily water demand = 100 gpcd = 378.5 Lpcd; (b) the slow sand filter's filtration rate is 3 million gallons per acre per day (MGAD) = 3 MGD/acre = 28.08 MLD/ha = 2,808 MLD/km^2; and (c) two slow sand filters are required. Each filter is able to treat the full water flow and one of the two filters is a standby unit.

1.12 Estimate roughly the size of a water supply pipe leading to a water distributing reservoir serving a small village of 2000 people assuming that (a) the water consumption rate is 100 gpcd = 378.5 Lpcd and (b) water velocity in the pipe = 3 ft/s = 0.91 m/s.

1.13 Determine the diameter of a water main to serve a residential area, assuming (a) an average water demand of 150 gpcd = 568 Lpcd; (b) population = 30,000; (c) fire flow requirement = 500 gpm = 2,082 L/min = 32 L/s; and (d) recommended water velocity = 3.5 ft/s = 1.07 m/s.

1.14 Roughly, what is the replacement cost of the waterworks of a city of 10,000 people?

1.15 Define the technical terms of (a) water supply system; (b) community water system; (c) nontransient noncommunity water system; d) transient noncommunity water system; and (e) watershed.

1.16 Define the technical terms of (a) collection works or systems; (b) purification works; (c) transmission works or systems; (d) distribution works or systems; and (e) impounding dams.

1.17 Define the technical terms of (a) aquifer; (b) water table; (c) infiltration galleries; (d) well; and (e) artesian.

1.18 Define the technical terms of (a) mixing basin or tank; (b) flocculation or reaction basins; (c) sedimentation basins; (d) slow sand filtration; and (e) rapid sand filtration.

1.19 Define the technical terms of (a) evaporation; (b) evapotranspiration; (c) aeration; (d) desalination; and (e) reverse osmosis.

1.20 Define the technical terms of (a) runoff; (b) fresh water; (c) saline and brackish waters; (d) precipitation; and (e) service reservoir or distribution reservoir.

REFERENCES

Al-Dhowalia, K. and Shammas, N. K., Leak detection and quantification of losses in a water network, *International Journal of Water Resources Development*, vol. 7, no. 1, pp. 30–38, 1991.

American Water Works Association, *Groundwater*, AWWA Publication, Denver, CO, 2003, 207 pp.

American Water Works Association, *Water Resources Planning*, AWWA Publication, Denver, CO, 2007, 378 pp.

American Water Works Association, *Water Resources*, AWWA Publication, Denver, CO, 2010, 210 pp.

American Water Works Association, *International Standard Units for Water and Wastewater Processes*, AWWA Publication, Denver, CO, 2011, 90 pp.

Department of Water Supply Web Site, County of Maui, Hawaii, http://mauiwater.org/, 2013.

Fair, G. M., Geyer, J. C., and Okun, D. A., *Water and Wastewater Engineering*, Vol. 1: Water Supply and Wastewater Removal, John Wiley & Sons, Inc., New York, 1966.

Fair, G. M., Geyer, J. C., and Okun, D. A., *Elements of Water Supply and Wastewater Disposal*, John Wiley & Sons, Inc., New York, 1971.

National Resources Conservation Service, U.S. Department of Agriculture, *Water Supply Forecasting*, http://www.wcc.nrcs.usda.gov/wsf/, 2013.

Orlob, G. T. and Lindorf, M. R., Cost of water treatment in California, *Journal of American Water Works Association*, vol. 50, no. 45, pp. 45–55, 1958.

Quraishi, A., Shammas, N. K., and Kadi, H., Analysis of per capita household water demand for the city of Riyadh, Saudi Arabia, *Arabian Journal for Science and Technology*, vol. 15, no. 4, pp. 539–552, 1990.

Shammas, N. K., Wastewater management and reuse in housing projects, in *Water Reuse Symposium IV, Implementing Water Reuse*, AWWA Research Foundation, Denver, CO, August 2–7, 1987, pp. 1363–1378.

Shammas, N. K. and Al-Dhowalia, K., Effect of pressure on leakage rate in water distribution networks, *Journal of Engineering Sciences*, vol. 5, no. 2, pp. 155–312, 1993.

Shammas, N. K. and El-Rehaili, A., Wastewater Engineering, in *Textbook on Wastewater Treatment Works and Maintenance of Sewers and Pumping Stations*, General Directorate of Technical Education and Professional Training, Institute of Technical Superintendents, Riyadh, Kingdom of Saudi Arabia, 1988.

U.S. Army Corps of Engineers, Yearly average cost index for utilities, in *Civil Works Construction Cost Index System Manual*, 1110-2-1304, U.S. Army Corps of Engineers, Washington, DC. http://www.nww.usace.army.mil/Missions/CostEngineering.aspx (2014).

U.S. Environmental Protection Agency, *Drinking Water and Ground Water Statistics for 2008*, EPA 816-K-08-004, Washington, DC, 2008.

U.S. Environmental Protection Agency, *Drinking Water Data*, Drinking water data tables available at http://www.epa.gov/safewater/data/getdata.html, 2012.

Wang, L. K., Hung, Y. T., and Shammas, N. K. (editors), *Physicochemical Treatment Processes*, Humana Press, Totowa, NJ, 2005, p. 723.

Wang, L. K., Hung, Y. T., and Shammas, N. K. (editors), *Advanced Physicochemical Treatment Processes*, Humana Press, Totowa, NJ, 2006, p. 690.

Wang, L. K., Hung, Y. T., and Shammas, N. K. (editors), *Advanced Physicochemical Treatment Technologies*, Humana Press, Totowa, NJ, 2007, p. 710.

Wang, L. K., Chen, J. P., Hung, Y. T., and Shammas, N. K. (editors), *Membrane and Desalination Technologies*, Humana Press, Totowa, NJ, 2011, p. 716.

World Health Organization, *Water, Sanitation and Health, Facts and Figures*, http://www.who.int/water_sanitation_health/publications/facts2004/en/index.html, 2004.

World Water Council Web Site, http://www.worldwatercouncil.org/index.php?id=23, 2014.