CHAPTER 1

WATER SUPPLY

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INTRODUCTION

A primary requisite for good health is an adequate supply of water that is of satisfactory sanitary quality. It is also important that the water be attractive and palatable to induce its use; otherwise, consumers may decide to use water of doubtful quality from a nearby unprotected stream, well, or spring. Where a municipal water supply passes near a property, the owner of the property should be urged to connect to it because such supplies are usually under competent supervision.

When a municipal water supply is not available, the burden of developing a safe water supply rests with the owner of the property. Frequently, private supplies are so developed and operated that full protection against dangerous or objectionable pollution is not afforded. Failure to provide satisfactory water supplies in most instances must be charged either to negligence or ignorance because it generally costs no more to provide a satisfactory installation that will meet good health department standards.

The following definitions are given in the National Drinking Water Regulations as amended through July, 2002:

Public water system means either a community or noncommunity system for the provision to the public of water for human consumption through pipes or other constructed conveyances, if such system has at least 15 service connections, or regularly serves an average of at least 25 individuals daily at least 60 days out of the year. Such a term includes (1) any collection, treatment, storage, and distribution facilities under the control of the operator of such system and used primarily in connection with such system, and

(2) any collection or pretreatment storage facilities not under such control which are used primarily in connection with such system.

A *community water system* has at least 15 service connections used by year-round residents, or regularly serves at least 25 year-round residents. These water systems generally serve cities and towns. They may also serve special residential communities, such as mobile home parks and universities, which have their own drinking water supply.

A *noncommunity water system* is a public water system that is not a community water system, and can be either a "transient noncommunity water system" (TWS) or a "non-transient noncommunity water system" (NTNCWS). TWSs typically serve travelers and other transients at locations such as highway rest stops, restaurants, and public parks. The system serves at least 25 people a day for at least 60 days a year, but not the same 25 people. On the other hand, NTNCWSs serve the same 25 persons for at least 6 months per year, but not year round. Some common examples of NTNCWSs are schools and factories (or other workplaces) that have their own supply of drinking water and serve 25 of the same people each day.

In 2007 there were approximately 156,000 public water systems in the United States serving water to a population of nearly 286 million Americans. There were approximately 52,110 community water systems, of which 11,449 were surface water supplies and 40,661 were groundwater supplies. There were 103,559 noncommunity water systems, of which 2557 were surface water supplies and 101,002 were groundwater supplies. Of the community water systems, 43,188 are small systems that serve populations less than 3300; 4822 are medium systems and serve populations between 3300 and 10,000; and 4100 are large systems serving populations over 10,000. In terms of numbers, the small and very small community and noncommunity water systems represent the greatest challenge to regulators and consultants—both contributing to over 88 percent of the regulatory violations in 2007.[1]

In addition to public water systems, the U.S. Geological Survey estimated that 43.5 million people were served by their own individual water supply systems in 2000. These domestic systems are—for the most part—unregulated by either state or county health departments.[2]

A survey made between 1975 and 1977 showed that 13 to 18 million people in communities of 10,000 and under used individual wells with high contamination rates.[3] The effectiveness of state and local well construction standards and health department programs has a direct bearing on the extent and number of contaminated home well-water supplies in specific areas.

A safe and adequate water supply for 2.4 billion people,[4] about one-third of the world's population, is still a dream. The availability of any reasonably clean water in the less-developed areas of the world just to wash and bathe would go a long way toward the reduction of such scourges as scabies and other skin diseases, yaws and trachoma, and high infant mortality. The lack of safe water makes high incidences of shigellosis, amebiasis, schistosomiasis,* leptospirosis, infectious hepatitis, giardiasis, typhoid, and paratyphoid fever commonplace.[5] Ten million persons suffer from dracunculiasis or guinea worm disease in Africa and parts of Asia.[6] The World Health Organization (WHO) estimates that some 3.4 million people die each year from water-borne diseases caused by microbially contaminated water supplies or due to a lack of access to sanitation facilities. Tragically, over one half of these deaths are children under the age of five years old.[7] Three-fourths of all illnesses in the developing world are associated with inadequate water and sanitation.[8] It is believed that the provision of safe water supplies, accompanied by a program of proper excreta disposal and birth control, could vastly improve the living conditions of millions of people in developing countries of the world.[9] In 1982, an estimated 46 percent of the population of Latin America and the Caribbean had access to piped water supply and 22 percent had access to acceptable types of sewage disposal.[10]

The diseases associated with the consumption of contaminated water are discussed in Chapter 1 of *Environmental Engineering, Sixth Edition: Prevention and Response to Water-, Food-, Soil,- and Air-Borne Disease and Illness* and summarized in Table 1.4 of that volume.

Groundwater Pollution Hazard

Table 1.1 shows a classification of sources and causes of groundwater pollution. The 20 million residential cesspool and septic tank soil absorption systems alone discharge about 400 billion gallons of sewage per day into the ground, which in some instances may contribute to groundwater pollution. This is in addition to sewage from restaurants, hotels, motels, resorts, office buildings, factories, and other establishments not on public sewers.[11] The contribution from industrial and other sources shown in Table 1.1 is unknown. It is being inventoried by the EPA, and is estimated at 900 billion gal/year,[12] the EPA, with state participation, is also developing a groundwater protection strategy. Included in the strategy is the classification of all groundwater and protection of existing and potential drinking water sources and “ecologically vital” waters.

Groundwater pollution problems have been found in many states. Primarily, the main cause is organic chemicals, such as trichloroethylene, 1,1,1-trichloroethane, benzene, perchlorate, gasoline (and gasoline additives such as MTBE), pesticides and soil fumigants, disease-causing organisms, and nitrates. Other sources are industrial and municipal landfills; ponds, pits, and lagoons; waste oils and highway deicing compounds; leaking underground storage tanks and pipelines; accidental spills; illegal dumping; and abandoned oil and gas wells. With 146 million people in the United States dependent on groundwater

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*Two hundred million cases of schistosomiasis worldwide were estimated in 2004, spread mostly through water contact (Centers for Disease Control and Prevention).

TABLE 1.1 Classification of Sources and Causes of Groundwater Pollution Used in Determining Level and Kind of Regulatory Control

Wastes		Nonwastes	
Category I[a]	Category II[b]	Category III[c]	Category IV[d]
Land application of wastewater: spray irrigation, infiltration–percolation basins, overland flow	Surface impoundments: waste-holding ponds, lagoons, and pits	Buried product storage tanks and pipelines	Saltwater intrusion: seawater encroachment, upward coning of saline groundwater
Subsurface soil absorption systems: septic systems	Landfills and other excavations: landfills for industrial wastes, sanitary landfills for municipal solid wastes, municipal landfills	Stockpiles: highway deicing stockpiles, ore stockpiles	River infiltration
Waste disposal wells and brine injection wells	Water and wastewater treatment plant sludges, other excavations (e.g., mass burial of livestock)	Application of highway deicing salts	Improperly constructed or abandoned wells
Drainage wells and sumps	—	Product storage ponds	Farming practices (e.g., dryland farming)
Recharge wells	Animal feedlots	Agricultural activities: fertilizers and pesticides, irrigation return flows	
	Leaky sanitary sewer lines Acid mine drainage Mine spoil pipes and tailings	Accidental spills	

[a] Systems, facilities, or activities designed to discharge waste or wastewaters (residuals) to the land and groundwaters.

[b] Systems, facilities, or activities that may discharge wastes or wastewaters to the land and groundwaters.

[c] Systems, facilities, or activities that may discharge or cause a discharge of contaminants that are not wastes to the land and groundwaters.

[d] Causes of groundwater pollution that are not discharges.

Source: The Report to Congress, Waste Disposal Practices and Their Effects on Ground Water, Executive Summary, U.S. Environmental Protection Agency, Washington, DC, January 1977, p. 39.

sources for drinking water,* these resources must be protected from physical, chemical, radiological, and microbiological contamination.

Whereas surface water travels at velocities of feet per second, groundwater moves at velocities that range from less than a fraction of a foot per day to several feet per day. Groundwater organic and inorganic chemical contamination may persist for decades or longer and, because of the generally slow rate of movement of groundwater, may go undetected for many years. Factors that influence the movement of groundwater include the type of geological formation and its permeability, the rainfall and the infiltration, and the hydraulic gradient. The slow uniform rate of flow, usually in an elongated plume, provides little opportunity for mixing and dilution, and the usual absence of air in groundwater to decompose or break down the contaminants add to the long-lasting problem usually created. By contrast, dilution, microbial activity, surface tension and attraction to soil particles, and soil adsorptive characteristics might exist that could modify, immobilize, or attenuate the pollutant travel. More attention *must* be given to the *prevention* of ground-water pollution and to wellhead protection.

TRAVEL OF POLLUTION THROUGH THE GROUND

Identification of the source of well pollution and tracing the migration of the incriminating contaminant are usually not simple operations. The identification of a contaminant plume and its extent can be truly complex. Comprehensive hydrogeological studies and proper placement and construction of an adequate number of monitoring wells are necessary.

Geophysical methods to identify and investigate the extent and characteristics of groundwater pollution include geomagnetics, electromagnetics, electrical resistivity, ground-probing radar, and photoionization meters.[13] *Geomagnetics* uses an instrument producing a magnetic field to identify and locate buried metals and subsurface materials that are not in their natural or undisturbed state. *Electromagnetics* equipment measures the difference in conductivity between buried materials such as the boundaries of contaminated plumes or landfills saturated with leachate and uncontaminated materials. *Electrical resistivity* measures the resistance a material offers to the passage of an electric current between electric probes, which can be interpreted to identify or determine rock, clay and other materials, porosity, and groundwater limits. *Ground-probing radar* uses radar energy to penetrate and measure reflection from the water table and subsurface materials. The reflection from the materials varies with depth and the nature of the material, such as sandy soils versus saturated clays. *Photoionization meters* are used to detect the presence of specific volatile organic compounds such as gasoline, and methane in a landfill, through the use of shallow boreholes. Other detection methods are remote imagery and aerial photography, including infrared.

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[*] Ninety-eight percent of the rural population in the United States and 32 percent of the population served by municipal water systems use groundwater (U.S. Geological Survey, 2000).

Sampling for contaminants must be carefully designed and performed. Errors can be introduced: Sampling from an unrepresentative water level in a well, contamination of sampling equipment, and incorrect analysis procedure are some potential sources of error. The characteristics of a pollutant, the subsurface formation, the hydraulic conductivity of the aquifer affected, groundwater slope, rainfall variations, and the presence of geological fractures, faults, and channels make determination of pollution travel and its sampling difficult. Geophysical techniques can help, and great care must be used in determining the number, spacing, location, and depths of sampling wells and screen entry levels. As a rule, monitoring wells and borings will be required to confirm and sample subsurface contamination.

Since the character of soil and rock, quantity of rain, depth of groundwater, rate of groundwater flow, amount and type of pollution, absorption, adsorption, biological degradation, chemical changes, and other factors usually beyond control are variable, one cannot say with certainty through what thickness or distance sewage or other pollutants must pass to be purified. Microbiological pollution travels a short distance through sandy loam or clay, but it will travel indefinite distances through coarse sand and gravel, fissured rock, dried-out cracked clay, or solution channels in limestone. Acidic conditions and lack of organics and certain elements such as iron, manganese, aluminum, and calcium in soil increase the potential of pollution travel. Chemical pollution can travel great distances.

The Public Health Service (PHS) conducted experiments at Fort Caswell, North Carolina, in a sandy soil with groundwater moving slowly through it. The sewage organisms (coliform bacteria) traveled 232 feet, and chemical pollution as indicated by uranin dye traveled 450 feet.[14] The chemical pollution moved in the direction of the groundwater flow largely in the upper portion of the groundwater and persisted for 2-1/2 years. The pollution band did not fan out but became narrower as it moved away from the pollution source. It should be noted that in these tests there was a small draft on the experimental wells and that the soil was a sand of 0.14 mm effective size and 1.8 uniformity coefficient. It should also be noted that, whereas petroleum products tend to float on the surface, halogenated solvents gradually migrate downward.

Studies of pollution travel were made by the University of California using twenty-three 6-inch observation wells and a 12-inch gravel-packed recharge well. Diluted primary sewage was pumped through the 12-inch recharge well into a confined aquifer having an average thickness of 4.4 feet approximately 95 feet below ground surface. The aquifer was described as pea gravel and sand having a permeability of 1900 gal/ft^2/day. Its average effective size was 0.56 mm and uniformity coefficient was 6.9. The medium effective size of the aquifer material from 18 wells was 0.36 mm. The maximum distance of pollution travel was 100 feet in the direction of groundwater flow and 63 feet in other directions. It was found that the travel of pollution was affected not by the groundwater velocity but by the organic mat that built up and filtered out organisms, thereby preventing them from entering the aquifer. The extent of the pollution then regressed as the organisms died away and as pollution was filtered out.[15]

Butler, Orlob, and McGauhey[16] made a study of the literature and reported the results of field studies to obtain more information about the underground travel of harmful bacteria and toxic chemicals. The work of other investigators indicated that pollution from dry-pit privies did not extend more than 1 to 5 feet in dry or slightly moist fine soils. However, when pollution was introduced into the underground water, test organisms (*Balantidium coli*) traveled to wells up to 232 feet away.[17] Chemical pollution was observed to travel 300 to 450 feet, although chromate was reported to have traveled 1,000 feet in 3 years, and other chemical pollution 3 to 5 miles. Leachings from a garbage dump in groundwater reached wells 1,476 feet away, and a 15-year-old dump continued to pollute wells 2,000 feet away. Studies in the Dutch East Indies (Indonesia) report the survival of coliform organisms in soil 2 years after contamination and their extension to a depth of 9 to 13 feet, in decreasing numbers, but increasing again as groundwater was approached. The studies of Butler et al. tend to confirm previous reports and have led the authors to conclude "that the removal of bacteria from liquid percolating through a given depth of soil is inversely proportional to the particle size of the soil."[18]

Knowledge concerning viruses in groundwater is limited, but better methodology for the detection of viruses is improving this situation. Keswick and Gerba[19] reviewed the literature and found 9 instances in which viruses were isolated from drinking water wells and 15 instances in which viruses were isolated from beneath land treatment sites. Sand and gravel did not prevent the travel of viruses long distances in groundwater. However, fine loamy sand over coarse sand and gravel effectively removed viruses. Soil composition, including the presence of clay, is very important in virus removal, as it is in bacteria removal. The movement of viruses through soil and in groundwater requires further study. Helminth eggs and protozoa cysts do not travel great distances through most soils because of their greater size but can travel considerable distances through macropores and crevices. However, nitrate travel in groundwater may be a major inorganic chemical hazard. In addition, organic chemicals are increasingly being found in groundwater. See (1) "Removal of Gasoline, Fuel Oil, and Other Organics in an Aquifer"; (2) "Prevention and Removal of Organic Chemicals"; and (3) "Synthetic Organic Chemicals Removal" in Chapter 2.

When pumping from a deep well, the direction of groundwater flow around the well within the radius of influence, not necessarily circular, will be toward the well. Since the level of the water in the well will probably be 25 to 150 feet, more or less, below the ground surface, the drawdown cone created by pumping may exert an attractive influence on groundwater, perhaps as far as 100 to 2,000 feet or more away from the well, because of the hydraulic gradient, regardless of the elevation of the top of the well. The radius of the drawdown cone or circle of influence may be 100 to 300 feet or more for fine sand, 600 to 1,000 feet for coarse sand, and 1,000 to 2,000 feet for gravel. See Figure 1.1. In other words, distances and elevations of sewage disposal systems and other sources of pollution must be considered relative to the hydraulic gradient and elevation of the water level in the well, while it is being pumped. It must also be recognized that pollution can travel in three dimensions in all or part of the aquifer's vertical thickness, dependent on the contaminant viscosity and density, the formation transmissivity,

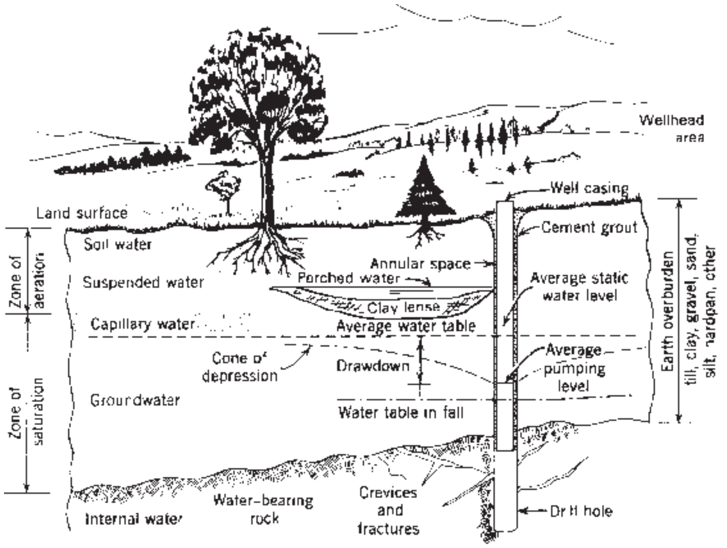

FIGURE 1.1 A geologic section showing groundwater terms. (*Source: Rural Water Supply*, New York State Department of Health, Albany, 1966.)

and the groundwater flow. Liquids lighter than water, such as gasoline, tend to collect above the groundwater table. Liquids heavier or more dense tend to pass through the groundwater and accumulate above an impermeable layer.

A World Health Organization (WHO) report reminds us that, in nature, atmospheric oxygen breaks down accessible organic matter and that topsoil (loam) contains organisms that can effectively oxidize organic matter.[20] However, these benefits are lost if wastes are discharged directly into the groundwater by way of sink holes, pits, or wells or if a subsurface absorption system is water-logged.

From the investigations made, it is apparent that the safe distance between a well and a sewage or industrial waste disposal system is dependent on many variables, including chemical, physical, and biological processes.[*] These four factors should be considered in arriving at a satisfactory answer:

1. The amount of sand, clay, organic (humus) matter, and loam in the soil, the soil structure and texture, the effective size and uniformity coefficient, groundwater level, and unsaturated soil depth largely determine the ability of the soil to remove microbiological pollution deposited in the soil.
2. The volume, strength, type, and dispersion of the polluting material, rainfall intensity and infiltration, and distance, elevation, and time for pollution to travel with relation to the groundwater level and flow and soil penetrated are important. Also important is the volume of water pumped and well drawdown.

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[*] A summary of the distances of travel of underground pollution is also given in Task Group Report, "Underground Waste Disposal and Control," *J. Am. Water Works Assoc.*, **49**, (October 1957): 1334–1341.

3. The well construction, tightness of the pump line casing connection, depth of well and well casing, geological formations penetrated, and sealing of the annular space have a very major bearing on whether a well might be polluted by sewage, chemical spills or wastes, and surface water.
4. The well recharge (wellhead) area, geology, and land use possibly permit groundwater pollution. Local land-use and watershed control is essential to protect and prevent pollution of well-water supplies.

Considerable professional judgment is needed to select a proper location for a well. The limiting distances given in Table 1.2 for private dwellings should

TABLE 1.2 Minimum Separation Distances (feet) from On-Site Wastewater Sources

Sources	To Well or Suction Line[a]	To Stream, Lake, or Water Course	To Property Line or Dwelling
House sewer (water-tight joints)	25 if cast iron pipe or equal, 50 otherwise	25	—
Septic tank	50	50	10
Effluent line to distribution box	50	50	10
Distribution box	100	100	20
Absorption field	100[b]	100	20
Seepage pit or cesspool	150[b] (more in coarse gravel)	100	20
Dry well (roof and footing)	50	25	20
Fill or built-up system	100	100	20
Evapotranspiration–absorption system	100	50	20
Sanitary privy pit	100	50	20
Privy, water-tight vault	50	50	10
Septic privy or aqua privy	50	50	10

[a] Water service and sewer lines may be in the same trench if cast-iron sewer with water-tight joints is laid at all points 12 in. below water service pipe; or sewer may be on dropped shelf at one side at least 12 in. below water service pipe, provided that sewer pipe is laid below frost with tight and root-proof joints and is not subject to settling, superimposed loads, or vibration. Water service lines under pressure shall not pass closer than 10 ft of a septic tank, absorption tile field, leaching pit, privy, or any other part of a sewage disposal system.

[b] Sewage disposal systems located of necessity upgrade or in the general path of drainage to a well should be spaced 200 ft or more away and not in the direct line of drainage. Wells require a minimum 20 ft of casing extended and sealed into an impervious stratum. If subsoil is coarse sand or gravel, do not use seepage pit; use absorption field with 12 in. medium sand on bottom of trench. Also require oversize drill hole and grouted well to a safe depth. See Table 1.15.

be used as a guide. Experience has shown them to be reasonable and effective in most instances *when coupled with a sanitary survey of the drainage area and proper interpretation of available hydrologic and geologic data and good well construction, location, and protection*.[21] See Figure 1.1 for groundwater terms. Well location and construction for public and private water systems should follow regulatory standards. See "Source and Protection of Water Supply" later in this chapter.

Disease Transmission

Water, to act as a vehicle for the spread of a specific disease, must be contaminated with the associated disease organism or hazardous chemical. Disease organisms can survive for days to years, depending on their form (cyst, ova) and environment (moisture, competitors, temperature, soil, and acidity) and the treatment given the wastewater. All sewage-contaminated waters must be presumed to be potentially dangerous. Other impurities, such as inorganic and organic chemicals and heavy concentrations of decaying organic matter, may also find their way into a water supply, making the water hazardous, unattractive, or otherwise unsuitable for domestic use unless adequately treated. The inorganic and organic chemicals causing illness include mercury, lead, chromium, nitrates, asbestos, polychlorinated biphenyl (PCB), polybrominated biphenyl (PBB), mirex, Kepone vinyl chloride, trichloroethylene, benzene, and others.

Communicable and noninfectious diseases that may be spread by water are discussed in Table 1.4 in Chapter 1 of *Environmental Engineering, Sixth Edition: Prevention and Response to Water-, Food-, Soil,- and Air-Borne Disease and Illness*.

WATER QUANTITY AND QUALITY

Water Cycle and Geology

The movement of water can be best illustrated by the hydrologic, or water, cycle shown in Figure 1.2. Using the clouds and atmospheric vapors as a starting point, moisture condenses out under the proper conditions to form rain, snow, sleet, hail, frost, fog, or dew. Part of the precipitation is evaporated while falling; some of it reaches vegetation foliage, the ground, and other surfaces. Moisture intercepted by surfaces is evaporated back into the atmosphere. Part of the water reaching the ground surface runs off to streams, lakes, swamps, or oceans whence it evaporates; part infiltrates the ground and percolates down to replenish the groundwater storage, which also supplies lakes, streams, and oceans by underground flow. Groundwater in the soil helps to nourish vegetation through the root system. It travels up the plant and comes out as transpiration from the leaf structure and then evaporates into the atmosphere. In its cyclical movement, part of the water is temporarily retained by the earth, plants, and animals to sustain life. The average annual precipitation in the United States is about 30 inches, of which 72 percent evaporates from water and land surfaces and transpires from

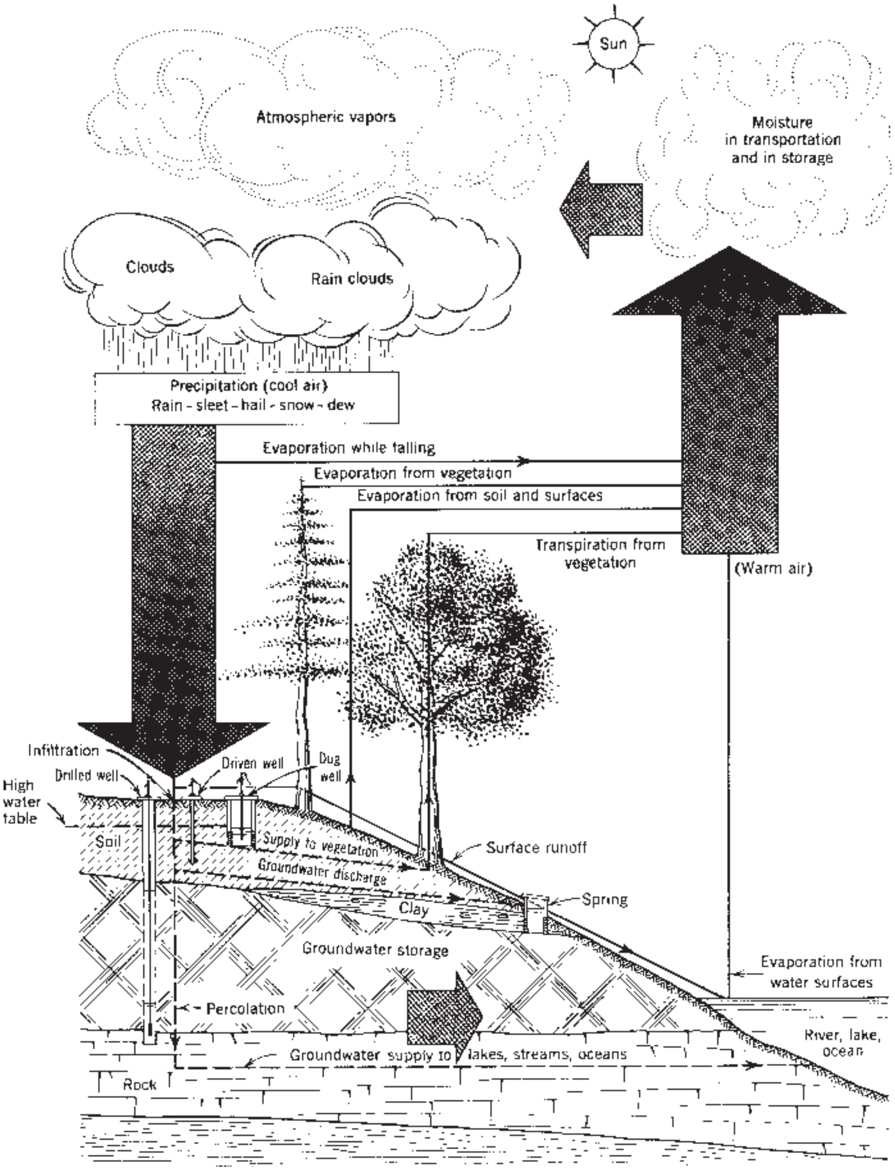

FIGURE 1.2 Figure hydrologic or (water) cycle. The oceans hold 317,000,000 mi^3 of water. Ninety-seven percent of the Earth's water is salt water; 3 percent of the Earth's fresh water is groundwater, snow and ice, fresh water on land, and atmospheric water vapor; 85 percent of the fresh water is in polar ice caps and glaciers. Total precipitation equals total evaporation plus transpiration. Precipitation on land equals 24,000 mi^3/year. Evaporation from the oceans equals 80,000 mi^3/year. Evaporation from lakes, streams, and soil and transpiration from vegetation equal 15,000 mi^3.

plants and 28 percent contributes to the groundwater recharge and stream flow.[22] See also "Septic Tank Evapotranspiration System," in Chapter 3.

The volume of fresh water in the hydrosphere has been estimated to be 8,400,000 mi^3 with 5,845,000 mi^3 in ice sheets and glaciers, 2,526,000 mi^3 in groundwater, 21,830 mi^3 in lakes and reservoirs, 3,095 mi^3 in vapors in the atmosphere, and 509 mi^3 in river water.[23]

When speaking of water, we are concerned primarily with surface water and groundwater, although rainwater and saline water are also considered. In falling through the atmosphere, rain picks up dust particles, plant seeds, bacteria, dissolved gases, ionizing radiation, and chemical substances such as sulfur, nitrogen, oxygen, carbon dioxide, and ammonia. Hence, rainwater is not pure water as one might think. It is, however, very soft. Water in streams, lakes, reservoirs, and swamps is known as *surface water*. Water reaching the ground and flowing over the surface carries anything it can move or dissolve. This may include waste matter, bacteria, silt, soil, vegetation, and microscopic plants and animals and other naturally occurring organic matter. The water accumulates in streams or lakes. Sewage, industrial wastes, and surface and groundwater will cumulate, contribute to the flow, and be acted on by natural agencies. On the one hand, water reaching lakes or reservoirs permit bacteria, suspended matter, and other impurities to settle out. On the other hand, microscopic as well as macroscopic plant and animal life grow and die, thereby removing and contributing impurities in the cycle of life.

Part of the water reaching and flowing over the ground infiltrates and percolates down to form and recharge the groundwater, also called underground water. In percolating through the ground, water will dissolve materials to an extent dependent on the type and composition of the strata through which the water has passed and the quality (acidity) and quantity of water. Groundwater will therefore usually contain more dissolved minerals than surface water. The strata penetrated may be unconsolidated, such as sand, clay, and gravel, or consolidated, such as sandstone, granite, and limestone. A brief explanation of the classification and characteristics of formations is given next.

Igneous rocks are those formed by the cooling and hardening of molten rock masses. The rocks are crystalline and contain quartz, feldspar, mica, hornblende, pyroxene, and olivene. Igneous rocks are not usually good sources of water, although basalts are exceptions. Small quantities of water are available in fractures and faults. Examples are granite, dioxite, gabbro, basalt, and syenite.

Sedimentary formations are those resulting from the deposition, accumulation, and subsequent consolidation of materials weathered and eroded from older rocks by water, ice, or wind and the remains of plants, animals, or material precipitated out of solution. Sand and gravel, clay, silt, chalk, limestone, fossils, gypsum, salt, peat, shale, conglomerates, loess, and sandstone are examples of sedimentary formations. Deposits of sand and gravel generally yield large quantities of water. Sandstones, shales, and certain limestones may yield abundant groundwater, although results may be erratic, depending on bedding planes and joints, density, porosity, and permeability of the rock.

Metamorphic rocks are produced by the alteration of igneous and sedimentary rocks, generally by means of heat and pressure. Gneisses and schists, quartzites, slates, marble, serpentines, and soapstones are metamorphic rocks. A small quantity of water is available in joints, crevices, and cleavage planes.

Karst areas are formed by the movement of underground water through carbonate rock fractures and channels, such as in limestone and gypsum, forming caves, underground channels, and sink holes. Because karst geology can be so porous, groundwater movement can be quite rapid (several feet per day). Therefore, well water from such sources is easily contaminated from nearby and distant pollution sources.

Glacial drift is unconsolidated sediment that has been moved by glacier ice and deposited on land or in the ocean.

Porosity is a measure of the amount of water that can be held by a rock or soil in its pores or voids, expressed as a percentage of the total volume. The volume of water that will *drain* freely out of a saturated rock or soil by gravity, expressed as a percentage of the total volume of the mass, is the *effective porosity* or *specific yield*. The volume of water retained is the *specific retention*. This is due to water held in the interstices or pores of the rock or soil by molecular attraction (cohesion) and by surface tension (adhesion). For example, plastic clay has a porosity of 45 to 55 percent but a specific yield of practically zero. In contrast, a uniform coarse sand and gravel mixture has a porosity of 30 to 40 percent with nearly all of the water capable of being drained out.

The *permeability* of a rock or soil, expressed as the standard coefficient of permeability or *hydraulic conductivity*, is the rate of flow of water at 60°F (16°C), in gallons per day, through a vertical cross-section of 1 ft^2, under a head of 1 foot, per foot of water travel. There is no direct relationship between permeability, porosity, and specific yield.

Transmissivity is the hydraulic conductivity times the saturated thickness of the aquifer.

Groundwater Flow

The flow through an underground formation can be approximated using Darcy's law,[24] expressed as $Q = KIA$, where

Q = quantity of flow per unit of time, gpd
K = hydraulic conductivity (water-conducting capacity) of the formation, gpd/ft^2 (see Table 1.3)
I = hydraulic gradient, ft/ft (may equal slope of groundwater surface)
A = cross-sectional area through which flow occurs, ft^2, at right angle to flow direction

For example, a sand aquifer within the floodplain of a river is about 30 feet thick and about a mile wide. The aquifer is covered by a confining unit of glacial till, the bottom of which is about 45 feet below the land surface. The difference in

TABLE 1.3 Porosity, Specific Yield, and Hydraulic Conductivity of Some Materials

Material	Porosity (vol %)	Specific Yield (%)	Hydraulic Conductivity or Permeability Coefficient,[a] K (gpd/ft^2)
Soils	55[b]	40[b]	10^{-5}–10 (glacial till)
	50–60[e]		
Clay	50[b]	2[b]	10^{-2}–10^{2} (silt, loess)
	45[d]	3[d]	10^{-6}–10^{-2} (clay)
	45–55[c]	1–10[e]	
Sand	25[b]	22[b]	1–10^{2} (silty sand)
	35[d]	25[d]	10–10^{4}
	30–40[c]	10–30[c]	
Gravel	20[b]	19[b]	10^{3}–10^{5}
	25[d]	22[d]	
	30–40[c]	15–30[c]	
Limestone	20[b]	18[b]	10^{-3}–10^{5} (fractured to cavernous, carbonate rocks)
	5[d]	2[d]	
	1–10[c]	0.5–5[e]	
Sandstone	11[b]	6[b]	10^{-4}–10 (fractured to semiconsolidated)
	15[d]	8[d]	
	10–20[c]	5–15[e]	
Shale	5[d]	2[d]	10^{-7}–10^{-3} (unfractured to fractured)
	1–10[c]	0.5–5[c]	
Granite	0.1[b]	0.09[b]	10^{-7}–10^{2} (unfractured to fractured, igneous and metamorphic)
	0.1[d]	0.5[d]	
	1[c]		
Basalt	11[b]	8[d]	10^{-7}–10^{5} (unfractured, fractured, to lava)

[a] *Protection of Public Water Supplies from Ground-Water Contamination*, Seminar Publication, EPA/625/4-85/016, Center for Environmental Research Information, Cincinnati, OH, September 1985, p. 11.

[b] R. C. Heath, *Basic Ground-Water Hydrology*, U.S. Geological Survey Paper 2220, U.S. Government Printing Office, Washington, DC, 1983.

[c] H. Ries and T. L. Watson, *Engineering Geology*, Wiley, New York, 1931.

[d] R. K. Linsley and J. B. Franzini, *Water Resources Engineering*, McGraw-Hill, New York, 1964.

[e] F. G. Driscoll, *Groundwater and Wells*, 2nd ed., Johnson Division, St. Paul, MN, 1986, p. 67.

Source: D. K. Todd, *Ground Water Hydrology*, 2nd ed., Wiley, New York, 1980.

water level between two wells a mile apart is 10 feet. The hydraulic-conductivity of the sand is 500 gpd/ft^2. Find Q:

$$\begin{aligned} Q &= KIA \\ &= 500\,\text{gpd/ft}^2 \times (10\,\text{ft}/5280\,\text{ft}) \times 5{,}280\,\text{ft} \times 30\,\text{ft} \\ &= 150{,}000\,\text{gpd} \end{aligned}$$

Also,

$$v = \frac{KI}{7.48n}$$

where

v = groundwater velocity, ft/day
n = effective porosity as a decimal

Find v:

$$\begin{aligned} v &= \frac{500\,\text{gpd} \times 10\,\text{ft}/5280\,\text{ft}}{7.48\,\text{g/ft}^3 \times 0.2} \\ &= 0.63\,\text{ft/day} \end{aligned}$$

Another example is given using Figure 1.3 and Darcy's law, expressed as

$$v = Ks$$

where

v = velocity of flow through an aquifer
K = coefficient of permeability (hydraulic conductivity)
s = hydraulic gradient

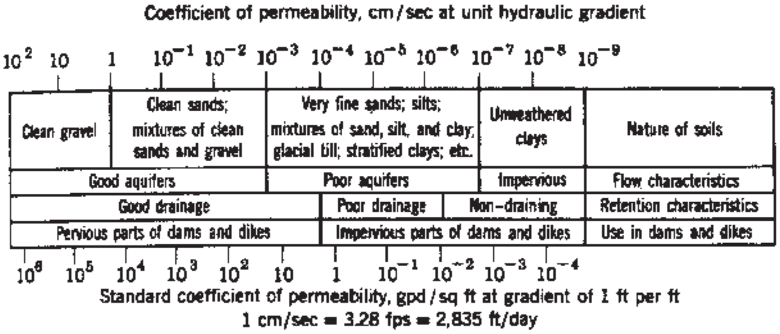

FIGURE 1.3 Magnitude of coefficient of permeability for different classes of soils. (*Source*: G. M. Fair, J. C. Geyer, and D. A. Okun, *Water and Wastewater Engineering*, Wiley, New York, 1966, pp. 9–13.)

Also,

$$Q = va$$

where

Q = discharge
a = cross-sectional area of aquifer

Example: (1) Estimate the velocity of flow (ft/day) and the discharge (gpd) through an aquifer of very coarse sand 1,000 feet wide and 50 feet thick when the slope of the groundwater table is 20 ft/m.

(2) Find the standard coefficient of permeability and the coefficient of transmissibility on the assumption that the water temperature is 60°F (16°C).

1. From Figure 1.3, choose a coefficient of permeability $K = 1.0\,\text{cm/sec} = 2835\,\text{ft/day}$. Because $s = 20/5280$, $v = 2835 \times 20/5280 = 11\,\text{ft/day}$ and $Q = 11 \times 1000 \times 50 \times 7.5 \times 10^{-6} = 4.1$ mgd.
2. The standard coefficient of permeability is $2{,}835 \times 7.5 = 2.13 \times 10^4$, and the coefficient of transmissibility becomes $2.13 \times 10^4 \times 50 = 1.06 \times 10^6$.

The characteristics of some materials are given in Table 1.3.

Groundwater Classification

The EPA has proposed the following groundwater classification system:

Class I: *Special Ground Water* are those which are highly vulnerable to contamination because of the hydrological characteristics of the areas in which they occur *and* which are also characterized by either of the following two factors:

- a. Irreplaceable, in that no reasonable alternative source of drinking water is available to substantial populations; or
- b. Ecologically vital, in that the aquifer provides the base flow for a particularly sensitive ecological system that, if polluted, would destroy a unique habitat.

Class II: *Current and Potential Sources of Drinking Water and Waters Having Other Beneficial Uses* are all other groundwaters which are currently used or are potentially available for drinking water or other beneficial use.

Class III: *Ground Waters Not Considered Potential Sources of Drinking Water and of Limited Beneficial Use* are ground waters which are heavily saline, with Total Dissolved Solids (TDS) levels over 10,000 mg/1, or are otherwise contaminated beyond levels that allow cleanup using methods employed in public water system treatment. These ground waters also must not migrate to Class I or Class II ground waters or have a discharge to surface water that could cause degradation.[25]

This classification system has been debated at great length. Some states have adopted stricter standards and eliminated class III, whereas others have added classifications.

Water Quality

The cleanest available sources of groundwater and surface water should be protected, used, and maintained for potable water supply purposes. Numerous parameters are used to determine the suitability of water and the health significance of contaminants that may be found in untreated and treated water. Watershed and wellhead protection regulations should be a primary consideration.

Microbiological, physical, chemical, and microscopic examinations are discussed and interpreted in this chapter under those respective headings. Water quality can be best assured by maintaining water clarity, chlorine residual in the distribution system, confirmatory absence of indicator organisms, and low bacterial population in the distributed water.[26]

Table 1.4 shows the standards for drinking water coming out of a tap served by a public water system. These are based on the National Primary Drinking Water Standards developed under the Safe Drinking Water Act of 1974 as amended in 1986 and 1996. The maximum contaminant level goals (MCLGs) in Table 1.4 are nonenforceable health goals that are to be set at levels at which no known or anticipated adverse health effects occur and that allow an adequate margin of safety. Maximum contaminant levels (MCLs) are enforceable and must be set as close to MCLGs as is feasible, based on the use of best technology, treatment techniques, analytical capabilities, costs, and other means. The EPA has based the MCLs on the potential health effects from the ingestion of a contaminant on the assumption that the effects observed (of a high dose) in animals may occur (at a low dose) in humans. This assumption has engendered considerable debate.

Secondary regulations, shown in Table 1.5, have also been adopted, but these are designed to deal with taste, odor, and appearance of drinking water and are not mandatory unless adopted by a state. Although not mandatory, these parameters have an important indirect health significance. Water that is not palatable is not likely to be used for drinking, even though reported to be safe, in both developed and underdeveloped areas of the world. A questionable or contaminated water source may then be inappropriately used. Water industry professionals in the United States should adhere to the USEPA primary and secondary standards without deviation or risk jeopardizing public health, either acutely (in the short term) or chronically (exposure over a long period.) It is also important to note that while each of the 50 states (and territories) must adopt and enforce USEPA's standards, they are free to either promulgate standards that are more stringent that USEPA or regulate contaminants that are of particular concern in their state. California, for example, regulates perchlorate even though there is no federal mandate to do so.

Tables 1.6 to 1.10 give World Health Organization (WHO) water-quality guidelines. It is not intended that the individual values in Tables 1.6 to 1.10 be

TABLE 1.4 Summary of National Primary Drinking Water Regulations, March 2008 (USEPA)

Name of Contaminant	Maximum Contaminant Level (MCL) (mg/1 unless noted)	Health Effects of Contaminant
	Inorganic Chemicals	
Antimony	0.006	Decreased longevity, blood effects
Arsenic	0.010	Cancer risk/cardiovascular and dermal effects
Asbestos (fiber length >10 μm)	7 million fibers per liter (MFL)	Lung tumors/cancer risk
Barium	2	Circulatory/gastrointestinal effects
Beryllium	0.004	Bone/lung effects/cancer risk
Cadmium	0.005	Liver/kidney/bone/circulatory effects
Chromium (total)	0.1	Liver/kidney/circulatory effects
Copper	Treatment technique (action limit 1.3)	Gastrointestinal/liver/kidney effects
Cyanide	0.2	Thyroid/neurologic effects
Fluoride	4	Skeletal effects
Lead	Treatment technique (action limit 0.015)	Cancer risk/kidney/nervous system effects Highly toxic to infants
Mercury (inorganic)	0.002	Kidney damage
Nickel	0.1	Nervous system/liver/heart effects/dermatitis
Nitrate (as N)	10	Methemoglobinemia (blue baby syndrome)/diuresis
Nitrite (as N)	1	Methemoglobinemia (blue baby syndrome)
Selenium	0.05	Nervous system/kidney/liver/circulatory effects
Thallium	0.002	Kidney/liver/brain/intestine effects
Radionuclides		
Combined radium-226 and radium-228	5 pCi/1	Cancer risk
Gross alpha (excluding radon and uranium)	15 pCi/1	Cancer risk

Beta particle and photon	4 mrem/year	Cancer risk
Radioactivity, uranium	0.030	Kidney effects/cancer risk
	Organic Chemicals	
SYNTHETIC ORGANIC COMPOUNDS		
2,3,7,8-TCDD (Dioxin)	0.00000003	Cancer risk/reproductive effects
2,4,5-TP (Silvex)	0.05	Liver/kidney effects
2,4-D	0.07	Nervous system/liver/kidney effects
Acrylamide	Treatment technique	Cancer risk/nervous system effects
Alachlor	0.002	Cancer risk/liver/kidney/spleen effects
Aldicarb[a]	0.003	Nervous system effects
Aldicarb sulfone[a]	0.003	Nervous system effects
Aldicarb sulfoxide[a]	0.004	Nervous system effects
Atrazine	0.003	Cardiologic effects/cancer risk/muscular degeneration
Carbofuran	0.04	Nervous/reproductive system effects
Chlordane	0.002	Cancer risk/liver/kidney/spleen effects
Dalapon	0.2	Kidney effects
Di(2-ethylhexyl)adipate	0.4	Liver/bone effects/cancer risk
1,2-Dibromo-3-chlorpropane (DBCP)	0.0002	Cancer risk/kidney/reproductive effects
Di(2-ethylhexyl)phthalate (DEHP)	0.006	Cancer risk/liver/reproductive effects
Dinoseb	0.007	Thyroid/reproductive organ effects
Diquat	0.02	Ocular effects
Endothall	0.1	Kidney/liver/gastrointestinal effects
Endrin	0.002	Liver effects
Epichlorohydrin	Treatment technique	Cancer risk/circulatory/stomach effects
Ethylene dibromide (EDB)	0.00005	Cancer risk/liver/heart/kidney/nervous system effects
Glyphosate	0.7	Kidney/reproductive effects

(*continues*)

TABLE 1.4 (*continued*)

Name of Contaminant	Maximum Contaminant Level (MCL) (mg/1 unless noted)	Health Effects of Contaminant
Heptachlor	0.0004	Cancer risk/liver effects
Heptachlor epoxide	0.0002	Cancer risk
Hexachlorobenzene	0.001	Cancer risk/liver/reproductive effects
Hexachlorocyclopentadiene (HEX)	0.05	Kidney/stomach effects
Lindane	0.0002	Kidney/liver/nervous/circulatory effects
Methoxychlor	0.04	Kidney/liver/nervous/developmental effects
Oxamyl (Vydate)	0.2	Nervous system effects
PAHs (benzo[*a*]pyrene)	0.0002	Cancer risk/developmental/reproductive effects
PCBs (polychlorinated biphenyls)	0.0005	Cancer risk/liver/gastrointestinal effects
Pentachlorophenol	0.001	Cancer risk/reproductive/liver/kidney effects
Picloram	0.5	Nervous system/liver effects
Simazine	0.004	Cancer risk/liver/kidney/thyroid effects
Toxaphene	0.003	Cancer risk/liver/kidney/nervous system effects
VOLATILE ORGANIC COMPOUNDS		
1,1-Dichloroethylene	0.007	Kidney/liver effects/cancer risk
1,1,1-Trichloroethane	0.2	Liver/circulatory/nervous system effects
1,1,2-Trichloroethane	0.005	Kidney/liver effects/cancer risk
1,2-Dichloroethane	0.005	Cancer risk
1,2-Dichloroprapane	0.005	Cancer risk/liver/kidney/gastrointestinal effects
1,2,4-Trichlorobenzene	0.07	Kidney/liver/adrenal gland effects
Benzene	0.005	Cancer risk/nervous system effects
Carbon tetrachloride	0.005	Cancer risk/liver effects
Chlorobenzene	0.1	Nervous system/liver effects
Cis-1,2-dichloroethylene	0.07	Liver/nervous/circulatory effects

Dichloromethane	0.005	Cancer risk/liver effects
Ethylbenzene	0.7	Kidney/liver/nervous system effects
Ortho-dichlorobenzene	0.6	Kidney/liver/blood cell/nervous system effects
Para-dichlorobenzene	0.075	Cancer risk/liver/circulatory effects
Styrene	0.1	Liver/nervous system effects/cancer risk
Tetrachloroethylene (PCE)	0.005	Cancer risk/liver/kidney/nervous system effects
Toluene	1	Kidney/liver effects
Trans-1,2-dichloroethylene	0.1	Nervous system/liver/circulatory effects
Trichloroethylene (TCE)	0.005	Cancer risk/liver effects
Vinyl chloride	0.002	Cancer risk/neurologic/liver effects
Xylenes (total)	10	kidney/liver/nervous system effects
	Microbiologic Contaminants	
TOTAL COLIFORM RULE (TCR)		
Total coliforms; fecal coliforms; *Escherichia coli*	Less than 40 samples/month; no more than one positive for total coliforms. If 40 samples or more per month, or more than 5% positive. Maximum contaminate level goal (MCLG) = 0 for total coliform, fecal coliform, and *E. coli*. Every sample containing total coliforms must be analyzed for fecal coliforms.	Presence of fecal coliform or *E. coli* may indicate potential contamination that can cause diarrhea, cramps, nausea, headaches, or other symptoms.
SURFACE WATER TREATMENT RULE		
Turbidity	Treatment technique	None; interferes with disinfection
Giardia	Treatment technique (MCLG = 0)	Giardiasis
Enteric Viruses	Treatment technique (MCLG = 0)	Gastrointestinal and other viral infections
Legionella	Treatment technique (MCLG = 0)	Legionnaire's disease
Heterotrophic plate count (HPC)	Treatment technique (MCLG = none)	Gastrointestinal infections
INTERIM ENHANCED SURFACE WATER TREATMENT RULE (IESWTR)		
Turbidity	Treatment technique	None; interferes with disinfection
Cryptosporidium	Treatment technique (MCLG = 0)	Cryptosporidiosis

(*continues*)

TABLE 1.4 (*continued*)

Name of Contaminant	Maximum Contaminant Level (MCL) (mg/1 unless noted)	Health Effects of Contaminant
FILTER BACKWASH RULE		
Cryptosporidium	Treatment technique (MCLG = 0)	Cryptosporidiosis
LONG TERM 2 ENHANCED SURFACE WATER TREATMENT RULE (LT2ESWTR)		
Cryptosporidium	Treatment technique (MCLG = 0) PWSs to monitor for cryptosporidium between 2006–2010 (staggered by system size). Additional treatment (if necessary) in place by 2012-2014.	Cryptosporidiosis
Giardia	Treatment technique (MCLG = 0)	Giardiasis
Viruses	Treatment technique (MCLG = 0)	Gastrointestinal and other viral infections
Disinfectants and Disinfection By-Products: Stage 1,2 D/DBPR DISINFECTANTS		
Chlorine	Maximum disinfectant residual level (MRDL)-4.0 (as Cl_2)	Eye/nose irritation, stomach discomfort
Chloramines	MRDL-4.0 (as Cl_2)	Hemolytic anemia in dialysis
Chlorine dioxide	MRDL-0.8 (as ClO_2)	Anemia; nervous system effects
DISINFECTION BY-PRODUCTS		
Total trihalomethanes (TTHMs)	0.080	Cancer risk/reproductive effects
Haloacetic acids (HAA5)	0.060	Cancer risk
Chlorite	1.0	Cancer risk
Bromate	0.010	Cancer risk/nervous system/liver effects
Total organic carbon (TOC)	Treatment technique	

[a] Aldicarb and metabolites are presently stayed, pending reproposal.

TABLE 1.5 Secondary Drinking Water Regulations, 2008 (USEPA)

Contaminant	Effect	Level
pH	Water should not be to acidic or too basic.	6.5–8.5
Aluminum	Colored water	0.05–0.2 mg/l
Chloride	Taste and corrosion of pipes	250 mg/1
Copper	Taste and staining of porcelain	1 mg/1
Foaming agents	Aesthetic	0.5 mg/1
Sulfate	Taste and laxative effects	250 mg/1
Total dissolved solids (hardness)	Taste and possible relation between low hardness and cardiovascular disease, also an indicator of corrosivity (related to lead levels in water); can damage plumbing and limit effectiveness of soaps and detergents	500 mg/1
Silver	Skin and eye discoloration	0.1 mg/l
Zinc	Taste	5 mg/1
Fluoride	Dental fluorosis (a brownish discoloration of the teeth)	2 mg/1
Color	Aesthetic	15 color units
Corrosivity	Aesthetic and health related (corrosive water can leach pipe materials, such as lead, into the drinking water)	Noncorrosive
Iron	Taste	0.3 mg/1
Manganese	Taste	0.05 mg/1
Odor	Aesthetic	3 threshold odor number

Source: U.S. Environmental Protection Agency, Fact Sheet, Office of Ground Water and Drinking Water, Washington, DC, March 2008.

used directly. Guideline values in the tables must be used and interpreted in conjunction with the information contained in the appropriate sections of Chapters 2 to 5 of *Guidelines for Drinking-Water Quality*, 2nd ed., volume 2, WHO, Geneva, 1996, 1998. Water treatment plant designers, operators and regulators worldwide should evaluate their water-quality goals and strive to produce the best water quality possible given the available technology, regardless of regulatory parameters.

TABLE 1.6 Microbiological and Biological Quality (WHO)

	Unit	Guideline Value	Remarks
		I. Microbiological Quality	
A. PIPED WATER SUPPLIES			
A.1 Treated Water Entering Distribution System			
Fecal coliforms	Number/100 ml	0	Turbidity <1 NTU; for disinfection with chlorine, pH preferably <8.0; free chlorine residual 0.2–0.5 mg/l following 30 min (minimum) contact.
Coliform organisms	Number/100 ml	0	—
A.2 Untreated Water Entering Distribution System			
Fecal coliforms	Number/100 ml	0	
Coliform organisms	Number/100 ml	0	In 98% of samples examined throughout the year, in the case of large supplies when sufficient samples are examined.
		3	In an occasional sample, but not in consecutive samples.
A.3 Water in Distribution System			
Fecal coliforms	Number/100 ml	0	—
Coliform organisms	Number/100 ml	0	In 95% of samples examined throughout year, in the case of large supplies when sufficient samples are examined.
		3	In an occasional sample, but not in consecutive samples.

B. UNPIPED WATER SUPPLIES			
Fecal coliforms	Number/100 ml	0	
Coliform organisms	Number/100 ml	10	Should not occur repeatedly; if occurrence is frequent and if sanitary protection cannot be improved, an alternative source must be found if possible.
C. BOTTLED DRINKING WATER			
Fecal coliforms	Number/100 ml	0	Source should be free from fecal contamination.
Coliform organisms	Number/100 ml	0	—
D. EMERGENCY WATER SUPPLIES			
Fecal coliforms	Number/100 ml	0	Advise public to boil water in case of failure to meet guideline values.
Coliform organisms	Number/100 ml	0	—
Enteroviruses	—	No guideline value set	—
		II. Biological Quality	
Protozoa (pathogenic)	—	No guideline value set	—
Helminths (pathogenic)	—	No guideline value set	—
Free-living organisms (algae, others)	—	No guideline value set	—

Source: Guidelines for Drinking-Water Quality, Vol. 1: *Recommendations*, World Health Organization, Geneva, 1984, Table 1. Reproduced with permission.

TABLE 1.7 Inorganic Constituents of Health Significance (WHO)

Constituent	Unit	Guideline Value
Arsenic	mg/l	0.05
Asbestos	—	No guideline value
Barium	—	No guideline value
Beryllium	—	No guideline value
Cadmium	mg/l	0.005
Chromium	mg/l	0.05
Cyanide	mg/l	0.1
Fluoride[a]	mg/l	1.5
Hardness	—	No health-related guideline value
Lead	mg/l	0.05
Mercury	mg/l	0.001
Nickel	—	No guideline value
Nitrate	mg/l (N)	10
Nitrite	—	No guideline value
Selenium	mg/l	0.01
Silver	—	No guideline value
Sodium	—	No guideline value

[a] Natural or deliberately added; local or climatic conditions may necessitate adaptation.

Source: Guidelines for Drinking-Water Quality, Vol. 1: *Recommendations*, World Health Organization, Geneva, 1984, Table 2. Reproduced with permission.

National secondary drinking water regulations shown in Table 1.5 are federally nonenforceable regulations that control contaminants in drinking water affecting the aesthetic qualities related to public acceptance of drinking water. These levels represent reasonable goals for drinking water quality. States may establish higher or lower levels, which may be appropriate, depending on local conditions such as unavailability of alternate source waters or other compelling factors, provided that public health and welfare are not adversely affected.

It is recommended that the parameters in these regulations be monitored at intervals no less frequent than the monitoring performed for inorganic chemical contaminants listed in the National Primary Drinking Water Regulations as applicable to community water systems. More frequent monitoring would be appropriate for specific parameters such as pH, color, and odor under certain circumstances as directed by the state.

Sampling and Quality of Laboratory Data

Raw and finished water should be continually monitored. Prior arrangements should also be made for the treatment plant to be immediately notified by upstream dischargers in case of wastewater treatment plant operational failures or accidental releases of toxic or other hazardous substances. A water treatment plant should have a well-equipped laboratory, certified operator, and qualified chemist. Disinfectant residual, turbidity, and pH should be monitored continuously where

TABLE 1.8 Organic Constituents of Health Significance (WHO)

	Unit	Guideline Value	Remarks
Aldrin and dieldrin	μg/l	0.03	
Benzene	μg/l	10^a	
Benzol[*a*]pyrene	μg/l	0.01^a	
Carbon tetrachloride	μg/l	3^a	Tentative guideline value[b]
Chlordane	μg/l	0.3	—
Chlorobenzenes	μg/l	No health-related guideline value	Odor threshold concentration between 0.1 and 3 μg/l
Chloroform	μg/l	30^a	Disinfection efficiency must not be compromised when controlling chloroform content
Chlorophenols	μg/l	No health-related guideline value	Odor threshold concentration 0.1 μg/l
2,4-D	μg/l	100^c	
DDT	μg/l	1	
1,2-Dichloroethane	μg/l	10^a	
1,1-Dichloroethene[d]	μg/l	0.3^a	
Heptachlor and heptachlor epoxide	μg/l	0.1	
Hexachlorobenzene	μg/l	0.01^a	
Gamma-HCH (lindane)	μg/l	3	
Methoxychlor	μg/l	30	
Pentachlorophenol	μg/l	10	
Tetrachloroethene[e]	μg/l	10^a	Tentative guideline value[b]
Trichloroethene[f]	μg/l	30^a	Tentative guideline value[b]
2,4,6-Trichlorophenol	μg/l	$10^{a,\,c}$	Odor threshold concentration, 0.1 μg/l
Trihalomethanes		No guideline value	See chloroform

[a] These guideline values were computed from a conservative hypothetical mathematical model that cannot be experimentally verified and values should therefore be interpreted differently. Uncertainties involved may amount to two orders of magnitude (i.e., from 0.1 to 10 times the number).

[b] When the available carcinogenicity data did not support a guideline value but the compounds were judged to be of importance in drinking water and guidance was considered essential, a tentative guideline value was set on the basis of the available health-related data.

[c] May be detectable by taste and odor at lower concentrations.

[d] Previously known as 1,1-dichloroethylene.

[e] Previously known as tetrachloroethylene.

[f] Previously known as trichloroethylene.

Source: Guidelines for Drinking-Water Quality, Vol. 1: *Recommendations*, World Health Organization, Geneva, 1984, Table 3. Reproduced with permission.

TABLE 1.9 Aesthetic Quality (WHO)

Characteristic	Unit	Guideline Value	Remarks
Aluminum	mg/l	0.2	
Chloride	mg/l	250	
Chlorobenzenes and chlorophenols	—	No guideline value	These compounds may affect taste and odor.
Color	True color units (TCU)	15	
Copper	mg/l	1.0	
Detergents	—	No guideline value	There should not be any foaming or taste and odor problems.
Hardness	mg/l (as $CaCO_3$)	500	
Hydrogen sulfide	—	Not detectable by consumers	
Iron	mg/l	0.3	
Manganese	mg/l	0.1	
Oxygen, dissolved	—	No guideline value	
pH	—	6.5–8.5	
Sodium	mg/l	200	
Solids, total dissolved	mg/l	1000	
Sulfate	mg/l	400	
Taste and odor	—	Inoffensive to most consumers	
Temperature	—	No guideline value	
Turbidity	Nephelometric turbidity units (NTU)	5	Preferably <1 for disinfection efficiency.
Zinc	mg/l	5.0	

Source: Guidelines for Drinking-Water Quality, Vol. 1: *Recommendations*, World Health Organization, Geneva, 1984, Table 4. Reproduced with permission.

TABLE 1.10 Radioactive Constituents (WHO)

	Unit[a]	Guideline Value
Gross alpha activity	Bq/1	0.1
Gross beta activity	Bq/1	1

[a] *Notes:* (a) If the levels are exceeded, more detailed radionuclide analysis may be necessary, (b) Higher levels do not necessarily imply that the water is unsuitable for human consumption [a] One bequerel (Bq) = 2.7×10^{-11} curie.

Source: Guidelines for Drinking-Water Quality, Vol. 1: *Recommendations*, World Health Organization, Geneva, 1984, Table 5. Reproduced with permission.

possible. In addition to routine testing equipment, equipment at large plants usually include a zeta meter for coagulant dosing measurements, a nephelometer for turbidity readings, a flame spectrophotometer for measuring inorganic chemicals, and a gas chromatograph with spectrophotometer instrument to measure organic chemicals in low concentrations (micrograms per liter or less). The analytical methods for MCL determination approved by the EPA for volatile chemicals include gas chromatography and gas chromatography–spectrometry techniques. The MCLG for a probable human carcinogen is proposed to be “zero,” the limit of detection for regulatory purposes. The MCLGs are unenforceable health goals for public water systems that cause no known or adverse health effects and incorporate an adequate margin of safety. The MCL is an enforceable standard established in the primary drinking water regulations that takes economic factors into consideration, in addition to no unreasonable risk to health. It should be understood that failure to report the presence of certain chemicals or microorganisms does not mean they are not present if the laboratory does not examine for them. All examinations should be made in accordance with the procedures given in *Standard Methods for the Examination of Water and Wastewater*, latest edition or one approved by the EPA (see the Bibliography).

Water samples may be continuous (such as for turbidity or particle counting), grab (instantaneous), composite (an accumulation of grab samples of equal volume), or flow-weighted composite (proportional to volume of flow). Most drinking water samples are grab, although this can be misleading when sampling for organic chemicals or heavy metals. Wastewater samples are composite or flow-weighted composite. When sampling, laboratory collection procedures should be followed.

Drinking water samples should be collected at times of maximum water usage from representative locations including residences. The sampling tap should be clean, not leaking (except in the case of lead and copper monitoring), and flushed for two to three minutes before sample collection. A 1-inch air space should be left on top of the bottle for a bacteriological sample. The bottle should be completely filled for a chemical sample; there must be no air bubble at the top. A laboratory-prepared bottle should be used.

Examination of a nonrepresentative sample is a waste of the sample collector’s and the laboratory’s time. It will give misleading information that can lead to incorrect and costly actions, discredit the agency or organization involved, and destroy a legal action or research conclusion.

There is a tendency to collect more samples and laboratory data than are needed. The tremendous resources in money, manpower, and equipment committed to the proper preparation, collection, and shipment of the samples and to the analytical procedures involved are lost sight of or misunderstood. Actually, a few carefully selected samples of good quality can usually serve the intended purpose.

The purpose or use of the laboratory data should determine the number of samples and quality of the laboratory work. Data of high quality are needed for official reporting and to support enforcement action or support a health effects study, while data of lesser quality may be acceptable for trend, screening, or monitoring purposes. High-quality legal data must follow official sample collection, identification, shipment, and analytical procedures exactly and without deviation.

The goal of a quality assurance program is to obtain scientifically valid, defensible data of known precision and accuracy to fulfill the water and/or wastewater utility's responsibility to protect and enhance the nation's environment.[27]

The laboratory is an essential ingredient of the effectiveness of the environmental program. However, the laboratory must resist the temptation to become involved in program operation and regulation activities, since its function does not involve sanitary surveys, routine inspection, performance evaluation, program enforcement, responsibility, regulation continuity, and effectiveness. In addition, its limited resources would be misdirected and diluted to the detriment of its primary function. This does not mean that the laboratory should not be involved in training, treatment plant laboratory certification, and solving difficult water plant operational problems.

Sanitary Survey and Water Sampling

A sanitary survey is necessary to determine the reliability of a water system to continuously supply safe and adequate water to the consumer.[28] It is also necessary to properly interpret the results of water analyses and evaluate the effects of actual and potential sources of pollution on water quality. The value of the survey is dependent on the training and experience of the investigator. When available, one should seek the advice of the regulatory agency sanitary engineer or sanitarian. Watershed protection includes enactment of watershed rules and regulations and regular periodic surveillance and inspections. It, in effect, becomes epidemiological surveillance and is a study of environmental factors that may affect human health. Watershed rules and regulations are legal means to control land use that might cause pollution of the water draining off and into the watershed of the water supply source.

If the source of water is a natural or manmade lake, attention would be directed to the following, for each contributes distinctive characteristics to the water: entire drainage basin and location of sewage and other solid and liquid waste disposal or treatment systems; bathing areas; stormwater drains; sewer outfalls; swamps; cultivated areas; feed lots; sources of erosion, sediment and pesticides; and wooded areas, in reference to the pump intake. When water is obtained from a stream or creek, all land and habitation above the water supply intake should be investigated. This means inspection of the entire watershed drainage area so that actual and potential sources of pollution can be determined and properly evaluated and corrective measures instituted. All surface-water supplies must be considered of doubtful sanitary quality unless given adequate treatment, depending on the type and degree of pollution received.

Sanitary surveys have usually emphasized protection of surface-water supplies and their drainage areas. Groundwater supplies such as wells, infiltration galleries, and springs have traditionally been protected by proper construction and location (at an arbitrary “safe” distance from potential sources of pollution and not directly downgrade). The rule-of-thumb distance of 75, 100, or 200 feet, coupled with well construction precautions, has usually served this purpose in most instances, such as for on-site residential wells, in the absence of hydrogeological and engineering investigation and design. However, greater attention is being given to potential distant sources of pollution, especially chemical sources.

The 1996 amendments to the Safe Drinking Water Act require a more sophisticated approach referred to as wellhead protection of groundwater sources. The wellhead is defined as “the surface and subsurface area surrounding a water well or wellfield supplying a public water system through which contaminants are reasonably likely to move toward and reach such well or wellfield.”* Determination of the aquifer limits and the drainage area tributary to a well or wellfield, an infiltration gallery, or spring, and the reasonable time of potential contaminants’ travel, requires knowledge of the geological formations in the area and the groundwater movement in adjacent and distant tributary areas. In confined or artesian aquifers, this is not readily apparent. The water may originate nearby or at a considerable distance, depending on the extent to which the aquifer formation is confined, channeled, or fractured and on its depth. The U.S. Geological Survey and state geological and water resources agencies may be able to provide information on the local geology and the aquifers. Protection of the tributary wellhead area would require governmental land-use controls, watershed rules and regulations, water purveyor ownership, and public cooperation. To accomplish this, it is first necessary to geographically identify the wellhead area, including groundwater flow, and all existing and potential sources of contamination in that area. This must be supplemented by the controls mentioned, including enactment of watershed (wellhead) protection rules and regulations, and their enforcement. See ”Source and Protection of Water Supply,” later in this chapter.

The sanitary survey would include, in addition to the source as already noted, the potential for and effects of accidental chemical spills and domestic sewage or industrial waste discharges and leachate from abandoned and existing hazardous waste and landfill sites. Included in the survey would be inspection and investigation of the reservoir, intake, pumping station, treatment plant, and adequacy of each unit process; operation records; distribution system carrying capacity, head losses, and pressures; storage facilities; emergency source of water and plans to supply water in emergency; integrity of laboratory services; connections with other water supplies; and actual or possible cross-connections with plumbing fixtures, tanks, structures, or devices that might permit backsiphonage or backflow. Certification of operators, the integrity and competence of the person in charge of the plant, and adequacy of budgetary support are important factors. Consideration should also be given to land-use plans and the purchase of hydrogeologically sensitive areas and zoning controls.

[*] Also defined as the area between a well and the 99 percent theoretical maximum extent of the stabilized cone of depression. CFR Title 40, Subchapter D, Part 141, U.S. Government Printing Office, July 1999.

Water samples are collected as an adjunct to the sanitary survey as an aid in measuring the quality of the raw water and effectiveness of treatment given. Microbiological examinations; chemical, radiochemical, and physical analyses; and microscopic examinations may be made, depending on the sources of water, climate, geology, hydrology, waste disposal practices on the watershed, problems likely to be encountered, and purpose to be served. In any case, all samples should be properly collected, transported, and preserved as required, and tests should be made by an approved laboratory in accordance with the procedures provided in the latest edition of *Standard Methods for the Examination of Water and Wastewater*[29] or as approved by the EPA.

A sanitary technique and a glass or plastic sterile bottle supplied and prepared by the laboratory for the purpose should be used when collecting a water sample for bacteriological examination. Hands or faucet must not touch the edge of the lip of the bottle or the plug part of the stopper. The sample should be taken from a clean faucet that does not have an aerator or screen and that is not leaking or causing condensation on the outside. Flaming of the tap is optional. The water should be allowed to run for about two to three minutes to get a representative sample. To check for metals and bacteria in household plumbing, the sample must be taken as a "standing" sample without preliminary running of water. A household water softener or other treatment unit may introduce contamination. If a sample from a lake or stream is to be collected, the bottle should be dipped below the surface with a forward sweeping motion so that water coming in contact with the hands will not enter the bottle. When collecting a sample for bacteriological examination, there should be an air space in the bottle. When collecting samples of chlorinated water, the sample bottle should contain sodium thiosulfate to dechlorinate the water. It is recommended that all samples be examined promptly after collection and within 6 to 12 hours if possible. After 24 to 48 hours, examinations may not be reliable.

The chemical and physical analyses may be for industrial or sanitary purposes, and the determinations made will be either partial or complete, depending on the information desired. Water samples for inorganic chemical analyses are usually collected in 1-liter polyethylene containers, new or acid washed if previously used. Samples for lead in drinking water at a tap or from a drinking fountain should be collected in the morning before the system has been used and flushed out and also during the day when the water is being used. Samples for organic chemical analyses are usually collected in 40-ml glass vials or 1-liter glass bottles with Teflon-lined closure.[30] Special precautions are necessary to ensure collection of representative samples free of incidental contamination and without loss of volatile fractions.[31] Containers must be completely filled. A special preservative is added for certain tests, and delivery time to the laboratory is sometimes specified. Samples are also collected for selected tests to control routine operation of a water plant and to determine the treatment required and its effectiveness.

Samples for microscopic examination should be collected in clean, wide-mouth bottles having a volume of 1 or 2 liters from depths that will yield representative organisms. Some organisms are found relatively close to the surface, whereas others are found at middepth or near the bottom, depending on the food, type of organism, and clarity and temperature of the water. Microscopic examinations can determine the changing types, concentrations, and locations of microscopic organisms, control measures or treatment indicated, and time to start treatment. A proper program can prevent tastes and odors by eliminating the responsible organisms that secrete certain oils before they can cause the problem. In addition, objectionable appearances in a reservoir or lake are prevented and sedimentation and filter runs are improved. Attention should also be given to elimination of the conditions favoring the growth of the organisms. See also "Microscopic Examination" in this chapter and "Control of Microorganisms", in Chapter 2.

Sampling Frequency

The frequency with which source and distribution system water samples are collected and used for bacteriologic, chemical, radiologic, microscopic, and physical analyses is usually determined by the regulatory agency, the water quality historical record, plant operational control requirements, and special problems. Operators of public water systems and industrial and commercial water systems will want to collect more frequent but carefully selected samples and make more analyses to detect changes in raw water quality to better control treatment, plant operation, and product quality.

The number of distribution system samples is usually determined by the population served, quality of the water source, treatment, past history, and special problems. Table 1.11 shows the minimum required sampling frequency for coliform density at community water systems in the United States. If routine sampling results in a "positive" indication of coliform bacteria, repeat sampling must be performed to verify the presence of actual bacteria. Table 1.11a presents the number of repeat samples necessary to verify whether or not the system is contaminated. At noncommunity water supplies a sample is collected in each quarter during which the system provides water to the (traveling) public. The minimum sampling frequency recommended by the WHO is shown in Table 1.12. Sampling points should reflect the quality of the water in the distribution system and be at locations of greatest use.

Fecal coliforms/E. coli; Heterotrophic Bacteria (HPC)

- If any routine or repeat sample is total coliform positive, the system must also analyze that total coliform positive culture to determine if fecal coliforms or *E. coli* are present. If fecal coliforms or *E. coli* are detected, the system must notify the state before the end of the same business day, or, if detected after the close of business for the state, by the end of the next business day.
- If any repeat sample is fecal coliform or *E. coli* positive or if a fecal coliform- or *E. coli*-positive original sample is followed by a total coliform-positive repeat sample and the original total coliform-positive sample is not invalidated, it is an acute violation of the MCL for total coliforms.

TABLE 1.11 Total Coliform Sampling Requirements According to Population Served

Population Served	Minimum Number of of Routine Samples per Month[a]	Population Served	Minimum Number of Routine Samples per Month[a]
25–1000[b]	1[c]	59,001–70,000	70
1001–2500	2	70,001–83,000	80
2501–3300	3	83,001–96,000	90
3301–4100	4	96,001–130,000	100
4101–4900	5	130,001–220,000	120
4901–5800	6	220,001–320,000	150
5801–6700	7	320,001–450,000	180
6701–7600	8	450,001–600,000	210
7601–8500	9	600,001–780,000	240
8501–12900	10	780,001–970,000	270
12,901–17,200	15	970,001–1,230,000	300
17,201–21,500	20	1,230,001–1,520,000	330
21,501–25,000	25	1,520,001–1,850,000	360
25,001–33,000	30	1,850,001–2,270,000	390
33,00–41,000	40	2,270,001–3,020,000	420
41,001–50,000	50	3,020,001–3,960,000	450
50,001–59,000	60	3,960,001 or more	480

[a] In lieu of the frequency specified, a noncommunity water system (NCWS) using groundwater and serving 1000 persons or fewer may monitor at a lesser frequency specified by the state until a sanitary survey is conducted and reviewed by the state. Thereafter, NCWS using groundwater and serving 1,000 persons or fewer must monitor in each calendar quarter during which the system provides water to the public, unless the state determines that some other frequency is more appropriate and notifies the system (in writing). Five years after promulgation, NCWSs using groundwater and serving 1,000 persons or fewer must monitor at least once a year. A NCWSs using surface water or groundwater under the direct influence of surface water, regardless of the number of persons served, must monitor at the same frequency as a like-sized community water system (CWS). A NCWS using groundwater and serving more than 1000 persons during any month must monitor at the same frequency as a like-sized CWS, except that the state may reduce the monitoring frequency for any month the system serves 1,000 persons or fewer.

[b] Include public water systems that have at least 15 service connections but serve fewer than 25 persons.

[c] For CWS serving 25–1,000 persons, the state may reduce this sampling frequency if a sanitary survey conducted in the last 5 years indicates that the water system is supplied solely by a protected groundwater source and is free of sanitary defects. However, in no case may the state reduce the frequency to less than once a quarter.

Source: Fact Sheet, Drinking Water Regulations under the Safe Drinking Water Act, Office of Drinking Water, U.S. Environmental Protection Agency, Washington, DC, May 1990, p. 22.

TABLE 1.11a Monitoring and Repeat Sample Frequency after Total Coliform-Positive Routine Sample

Samples per Month	Number of Repeat Samples[a]	Number of Routine Samples Next Month[b]
1	4	5
2	3	5
3	3	5
4	3	5
5 or greater	3	See Table 1.11

[a] Number of repeat samples in the same month for each total coliform-positive routine sample.

[b] Except where state has invalidated the original routine sample, substitutes an on-site evaluation of the problem or waives the requirement on a case-by-case basis.

Source: Fact Sheet, Drinking Water Regulations under the Safe Drinking Water Act, Office of Drinking Water, U.S. Environmental Protection Agency, Washington, DC, December 1990, pp. 23–25.

TABLE 1.12 Distribution System Sampling

Population Served	Minimum Number of Samples
<5000	1 per month
5000–100,000	1 per 5000 population per month
100,000	1 per 10,000 population per month

Source: Guidelines for Drinking-Water Quality, Vol. 1: *Recommendations*, World Health Organization, Geneva, 1984, p. 24.

- The state has the discretion to allow a water system, on a case-by-case basis, to forgo fecal coliform or *E. coli* testing on total coliform-positive samples if the system complies with all sections of the rules that apply when a sample is fecal coliform positive.
- State invalidation of the routine total coliform-positive sample invalidates subsequent fecal coliform- or *E. coli*-positive results on the same sample.
- Heterotrophic bacteria can interfere with total coliform analysis. Therefore, if the total coliform sample produces (1) a turbid culture in the absence of gas production using the multiple-tube fermentation (MTF) technique; (2) a turbid culture in the absence of an acid reaction using the presence–absence (PA) coliform test; or (3) confluent growth or a colony number that is "too numerous to count" using the membrane filter (MF) technique, the sample is invalid (unless total coliforms are detected, in which case the sample is valid). The system must collect another sample within 24 hours of being notified of the result from the same location as the original sample and have it analyzed for total coliforms.

Analytical Methodology

- Total coliform analyses are to be conducted using the 10-tube MTF technique, the MF Technique, the PA coliform test, or the minimal media ONPG-MUG test (Autoanalysis Colilert System). The system may also use the five-tube MTF technique (20-ml sample portions) or a single culture bottle containing the MTF medium as long as a 100-ml water sample is used in the analysis.
- A 100-ml standard sample volume must be used in analyzing for total coliforms, regardless of the analytical method used.

Invalidation of Total Coliform-Positive Samples

- All total coliform-positive samples count in compliance calculations, except for those samples invalidated by the state. Invalidated samples do not count toward the minimum monitoring frequency.
- A state may invalidate a sample only if (1) the analytical laboratory acknowledges that improper sample analysis caused the positive result; (2) the system determines that the contamination is a domestic or other nondistribution system plumbing problem; or (3) the state has substantial grounds to believe that a total coliform-positive result is due to some circumstance or condition not related to the quality of drinking water in the distribution system if (a) this judgment is explained in writing, (b) the document is signed by the supervisor of the state official who draws this conclusion, and (c) the documentation is made available to the EPA and the public.

Variances and Exemptions: None Allowed Sanitary Surveys

- Periodic sanitary surveys are required for all systems collecting fewer than five samples a month every 5 years at community water systems and every 10 years at noncommunity water systems using protected and disinfected groundwater.

Water Analyses

All analyses should be made in accordance with *Standard Methods*[32] in order to provide confidence in the analytical results. As indicated previously, the interpretation of water analyses is based primarily on the sanitary survey of the water system and an understanding of the criteria used in the regulatory development of the drinking water standards. A water supply that is coagulated and filtered would be expected to be practically clear, colorless, and free of iron, whereas the presence of some turbidity, color, and iron in an untreated surface water supply may be accepted as normal. A summary is given in this section of the constituents and concentrations considered significant in water examinations. Other compounds and elements not mentioned are also found in water. The effectiveness of unit treatment processes can be measured using the tests for total coliforms, fecal coliforms, fecal streptococci, and the standard plate count 6 months prior to and 12 months after the process is put into use.

A properly developed, protected, and chlorinated well-water supply showing an absence of coliform organisms can usually be assumed to be free of viruses, protozoa, and helminths if supported by a satisfactory sanitary survey. This is not necessarily so with a surface-water supply. Chemical examinations are needed to ensure the absence of toxic organic and inorganic chemicals.

A final point: The results of a microbiological or chemical examination reflect the quality of the water only at the time of sampling and must be interpreted in the light of the sanitary survey. However, inorganic chemical examination results from well-water supplies are not likely to change significantly from day to day or week to week when collected under the same conditions. Nevertheless, any change is an indication of probable contamination and reason for investigation to determine the cause. The chemical characteristics of well water are a reflection of the geological formations penetrated. Some bacterial and chemical analyses are shown in Table 1.13.

Heterotrophic Plate Count — The Standard Plate Count

The standard plate count is the total colonies of bacteria developing from measured portions (two 1 ml and two 0.1 ml) of the water being tested, which have been planted in petri dishes with a suitable culture medium (agar) and incubated for 48 hours at 95°F (35°C). Bottled water is incubated at 35°C for 72 hours.[33] Only organisms that grow on the media are measured. Drinking water will normally contain some nonpathogenic bacteria; it is almost never sterile.

The test is of significance when used for comparative purposes under known or controlled conditions to show changes from the norm and determine if follow-up investigation and action are indicated. It can monitor changes in the quality (organic nutrients) of the water in the distribution system and storage reservoirs; it can be used to detect the presence of *Pseudomonas, Flavobacterium*, and other secondary invaders that could pose a health risk in the hospital environment; it can call attention to limitations of the coliform test when the average of heterotrophic plate counts in a month exceeds 100 to 500 per ml; it can show the effectiveness of distribution system residual chlorine and possible filter breakthrough; it can show distribution system deterioration, main growth, and sediment accumulation; and it can be used to assess the quality of bottled water. Large total bacterial populations (greater than 1,000 per ml) may also support or suppress growth of coliform organisms. Taste, odor, or color complaints may also be associated with bacterial or other growths in mains or surface-water sources.[34] Bacterial counts may increase in water that has been standing if nutrients are present, such as in reservoirs after copper sulfate treatment and algae destruction or in dead-end mains. These are of no sanitary significance. Mesophilic fungi and actinomycetes, sometimes associated with tastes and odors, may be found in treated water.

TABLE 1.13 Some Bacterial and Chemical Analyses

Source of Sample	Dug Well	Lake	Reservoir	Deep Well	Deep Well
Time of year	—	April	October	—	—
Treatment	None	Chlorine	None	None	None
Bacteria per milliliters agar, 35°C, 24 hr	—	3	—	1	>5000
Coliform MPN per 100 ml	—	<2.2	—	<2.2	≥ 2400
Color, units	0	15	30	0	0
Turbidity, units	Trace	Trace	Trace	Trace	5.0
Odor					
Cold	2 vegetative	2 aromatic	1 vegetative	1 aromatic	3 disagreeable
Hot	2 vegetative	2 aromatic	1 vegetative	1 aromatic	3 disagreeable
Iron, mg/1	0.15	0.40	0.40	0.08	0.2
Fluorides, mg/1	<0.05	0.005	—	—	—
Nitrogen as ammonia, free, mg/1	0.002	0.006	0.002	0.022	0.042
Nitrogen as ammonia, albuminoid, mg/1	0.026	0.128	0.138	0.001	0.224
Nitrogen as nitrites, mg/1	0.001	0.001	0.001	0.012	0.030
Nitrogen as nitrates, mg/1	0.44	0.08	0.02	0.02	0.16
Oxygen consumed, mg/1	1.1	2.4	7.6	0.5	16.0
Chlorides, mg/1	17.0	5.4	2.2	9.8	6.6
Hardness (as $CaCO_3$), total, mg/1	132.0	34.0	84.0	168.0	148.0
Alkalinity (as $CaCO_{,3}$), mg/1	94.0	29.0	78.0	150.0	114.0
pH value	7.3	7.6	7.3	7.3	7.5

Bacterial Examinations

The bacterial examinations for drinking water quality should always include, as a minimum, tests for total organisms of the coliform group, which are *indicative* of fecal contamination or sewage pollution. They are a normal inhabitant of the intestinal tract of humans and other animals. The goal is no coliform organisms in drinking water. In the past, the coliform group was referred to as the *B. coli* group and the *coli–aerogenes* group. The count for the total coliform group of organisms may include *Escherichia coli*, which is most common in the feces of humans and other warm-blooded animals; *Klebsiella pneumoniae*,* which is

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*May have been identified in the past as *Aerobacter aerogenes*.

found in feces and sputum, on fresh vegetables, and in organically rich surface water; *Enterobacter cloacae*, which is found in feces of warm-blooded animals in smaller number than *E. coli*, also in pipe joints, soil, and vegetation; *Citrobacter freundii*, which is normally found in soil and water, also in feces of humans and other warm-blooded animals; and *Enterobacter aerogenes*, which is found in human and other warm-blooded animal feces, soil, pipe joints, and vegetation.* Coliforms are also found in slimes, pump leathers, swimming pool ropes, stormwater drainage, surface waters, and elsewhere.

The tests for fecal coliforms, *E. coli*, fecal streptococci, and *Clostridium perfringens* may be helpful in interpreting the significance of surface-water tests for total coliforms and their possible hazard to the public health. Tests for *Pseudomonas* spp. may indicate the condition in water mains.

Coliform bacteria are not normally considered disease organisms. However, pathogenic (enterotoxigenic) strains of *E. coli* have caused outbreaks of "traveler's diarrhea" and gastroenteritis in institutions and in communities associated with food, raw milk, water, or fomites. The enteropathogenic strains have been associated with outbreaks in newborn nurseries. The test for *E. coli* at 95°F (35°C) is recommended as being a more specific indicator of fecal contamination in Denmark, Belgium, England, France,[35] and the United States. More extensive laboratory procedures are needed to identify *E. coli* and the enteropathogenic *E. coli. Escherichia coli* makes up about 95 percent of the fecal coliforms.

The coliform group of organisms includes all of the aerobic and facultative anaerobic, gram-negative, non-spore-forming, rod-shaped bacteria that ferment lactose with acid and gas formation within 24 to 48 hours at 95° to 90°F (35°–37°C). This is the presumptive test that can be confirmed and completed by carrying the test further, as outlined in *Standard Methods*.[36] Coliform species identification is useful in interpreting the significance of the total coliform test where the cause is unclear. Differentiation can confirm the presence of *E. coli*, and hence fecal contamination, or other types of coliforms as previously explained. Prior to December 31, 1990, the results in the MTF were reported as the most probable number (MPN) of coliform bacteria, a statistical number most likely to produce the test results observed, per 100 ml of sample.

A review of the coliform rule by the EPA, as required by the 1986 amendment to the Safe Drinking Water Act, led to the development of a new regulatory standard effective December 31, 1990. This new standard is based on the presence or absence of total coliform bacteria rather than bacterial density. The new standard sets the MCL for total coliforms as follows:

Monthly Number of Samples	**MCL**
Fewer than 40	No more than 1 positive sample
40 or more	No more than 5.0% positive

**Enterobacter* and *Klebsiella* are not considered pathogenic to humans, but may be associated with disease-causing organisms found in feces.

In addition, an acute violation necessitates immediate public notification via broadcast media if a routine sample tests positive for total coliforms and for fecal coliforms or *E. coli* and any repeat sample tests positive for total coliforms or a routine sample tests positive for total coliforms and negative for fecal coliforms or *E. coli* and any repeat sample is positive for fecal coliforms or *E. coli*.

If the MTF method is used, the sample size is 100 ml. Either five 20-ml portions or ten 10-ml portions can be used. If any tube has gas formation, the sample is total coliform positive.

If the membrane filter technique is used, the coliform bacteria trapped on the filter produce dark colonies with a metallic sheen within 24 hour (18–22 hours) on an Endo-type medium containing lactose when placed in a 35°C incubator. The dark colonies are presumed to be of the coliform group and the sample is reported as coliform positive. The test can be carried further for coliform differentiation by following the procedure in *Standard Methods*.[37] Suspended matter, algae, and bacteria in large amounts interfere with the membrane filter (0.45 μm) procedure. Bacterial overgrowth on the filter would indicate an excessive bacterial population that should be investigated as to cause and significance.

For many years, the MTF test and the membrane filtration (MF) test have been the approved methods for detecting the presence of coliform organisms. Another test, known as the Colilert test, was approved by the EPA in 1989 for the presence or absence of total coliform. A 100-ml sample and one 100-ml tube with a specially prepared media or a set of five 10-ml tubes* are used to which the test water is added and incubated at 95 to 99°F (35°–37°C). A sterile technique must of course be used. The results are available within 24 hours or may be extended to 48 hours. The presence of coliform is shown by a color change to yellow, the absence by no color change. The presence of *E. coli* is also shown by fluorescence of the tube when viewed under ultraviolet (UV) light. Heterotrophic bacteria levels of 5,000 to 700,000 per ml did not interfere with the Colilert test.

The *fecal coliform test* involves incubation at 112°F (44.5°C) for 24 hours and measures mostly *E. coli* in a freshly passed stool of humans or other warm-blooded animals. A loop of broth from each positive presumptive tube incubated at 95°F (35°C) in the total coliform test is transferred to EC (*E. coli*) broth and incubated at 112°F (44.5°C) in a waterbath; formation of gas within 24 hours indicates the presence of fecal coliform and hence also possibly dangerous contamination. Maintenance of 112°F (44.5 ± 0.2°C) is critical. Nonfecal organisms generally do not produce gas at 112°F (44.5°C). The test has greatest application in the study of stream pollution, raw water sources, sea waters, wastewaters, and the quality of bathing waters. An average individual contributes about 2 billion coliform per day through excrement.

The *fecal streptococci* test (enterococci) uses special agar media incubated at 95°F (35°C) for 48 hours. Dark red to pink colonies are counted as fecal streptococci. They are also normally found in the intestinal tract of warm-blooded

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*Standard tables are used to determine the MPN when more than one tube is used.

animals, including humans. Most (about 80 percent) of the human fecal streptococci are *Streptococcus faecalis; Streptococcus bovis* is associated with cows, and *Streptococcus equinus* with horses. These organisms may be more resistant to chlorine than coliform and survive longer in some waters but usually die off quickly outside the host. If found, it would indicate recent pollution. An average individual contributes approximately 450 million *fecal streptococci* per day.

The test for *C. perfringens (Clostridium welchii)*, which is found in the intestines of humans and animals, may be of value in the examination of polluted waters and waters containing certain industrial wastes. Clostridia sporulate under unfavorable conditions and can survive indefinitely in the environment; they are more resistant than escherichia and streptococci. Therefore, their presence indicates past or possibly intermittent pollution.

In domestic sewage, the fecal coliform concentration is usually at least four times that of the fecal streptococci and may constitute 30 to 40 percent of the total coliforms. In stormwater and wastes from livestock, poultry, animal pets, and rodents, the fecal coliform concentration is usually less than 0.4 of the fecal streptococci. In streams receiving sewage, fecal coliforms may average 15 to 20 percent of the total coliforms in the stream. The presence of fecal coliform generally indicates fresh and possibly dangerous pollution. The presence of intermediate *aerogenes–cloacae* (IAC) subgroups of coliform organisms suggests past pollution or, in a municipal water supply, defects in treatment or in the distribution system.[38] A ratio of fecal coliforms to *C. perfringens* greater than 100 indicates sewage discharge.

The presence of any coliform organism in drinking water is a danger sign: It must be carefully interpreted in the light of water turbidity, chlorine residual, bacterial count, and sanitary survey, and it must be promptly eliminated. There may be some justification for permitting a low coliform density in developing areas of the world where the probability of other causes of intestinal diseases greatly exceeds those caused by water, as determined by epidemiological information. The lack of any water for washing promotes disease spread.

It must be understood and emphasized that the absence of coliform organisms or other indicators of contamination does not in and of itself ensure that the water is always safe to drink unless it is supported by a satisfactory, comprehensive sanitary survey of the drainage area, treatment unit processes, storage, and distribution system (including backflow prevention). Nor does the absence of coliforms ensure the absence of viruses, protozoa, or helminths unless the water is coagulated, flocculated, settled, gravity filtered, and chlorinated to yield a free residual chlorine of at least 0.5 mg/1, preferably for 1 hour before it is available for consumption. The WHO recommends a free residual chlorine of at least 0.5 mg/1 with a contact period of at least 30 minutes at a pH below 8.0 and a nephelometric turbidity unit (NTU) of 1 or less. A free ozone of 0.2 to 0.4 mg/1 for 4 minutes has been found to be effective to inactivate viruses in clean water (ref. 39, Vol. 2, p. 28). Chlorine dioxide and chloramine treatment may also be used. See "Disinfection," in Chapter 2.

Biological Monitoring

A seven-day biological toxicity test of raw water may be useful to measure chronic effects. Indicators may include the fathead minnow and *Ceriodaphnia*, their survival, growth rate, and reproduction. In some instances, biological monitoring will be more meaningful than environmental monitoring: It can measure the combined effect of air, water, and food pollutants on an organism or animal; this information can be more closely related to potential human health effects.

Virus Examination

The examination of water for enteroviruses has not yet been simplified to the point where the test can be made routinely for compliance monitoring, as for coliform. Viruses range in size from 0.02 to 0.1 μm. There are more than 100 different types of enteric viruses known to be infective. Fecal wastes may contain enteroviruses (echoviruses, polioviruses, and coxsackieviruses—groups A and B) as well as adenoviruses, reoviruses, rotaviruses, Norwalk viruses, and infectious hepatitis viruses (viral hepatitis A).

Enteroviruses may be more resistant to treatment and environmental factors than fecal bacteria, persist longer in the water environment, and remain viable for many months, dependent on temperature and other factors. Enteric viruses, such as protozoa (*Giardia lamblia, Entamoeba histolytica*, and *Cryptosporidium* spp.), may be present even if coliform are absent.

Normally, a large volume of water (100–500 gal) must be sampled and an effective system used to capture, concentrate, and identify viruses. Results may not be available until one or two weeks later.[39] Special analytical laboratory facilities and procedures are required. See *Standard Methods*.[40] A virus standard for drinking water has not been established. A goal of zero to not more than one plaque-forming unit (pfu) per 1,000 gal of drinking water has been suggested.

Since monitoring for enteric viruses is not feasible for routine control of water treatment plant operation, the EPA is requiring specific treatment, or the equivalent, of all surface waters and mandatory chlorination, or equivalent protection, of all groundwaters. Coagulation, flocculation, settling, and rapid sand filtration; slow sand filtration; and lime-soda softening process remove 99 percent or more of the viruses. A pH above 11 inactivates viruses.

Free chlorine is more effective than combined chlorine in inactivating viruses and is more effective at low pH. Turbidity can shield viruses and make chlorination only partially effective. Based on available information, the WHO considers treatment adequate if a turbidity of 1 NTU or less is achieved and the free residual chlorine is at least 0.5 mg/1 after a contact period of at least 30 minutes at a pH below 8.0. Prudence would dictate that water obtained from a source known to receive sewage wastes should be coagulated, flocculated, settled, filtered, and disinfected to produce at least 0.4 mg/1 free residual chlorine for 2 hours before delivery. Ozone is also an effective disinfectant for clean water if residuals of 0.2 to 0.4 mg/1 are maintained for 4 min, but the residual does not remain in the distribution system.[41] The EPA requires 99.99 percent removal and/or inactivation of enteric viruses.

Protozoa and Helminths Examination

The complex procedure to sample, collect, prepare, and positively identify the protozoan cysts of *Giardia lamblia* is impractical for the routine control of water treatment. Because of this, the EPA requires complete treatment of surface waters unless the absence of giardia cysts can be demonstrated and assured by other acceptable means. Sampling for giardia cysts usually involves the filtration of about 500 gal of the water through a 1-μm-pore-size cartridge filter at a rate of about 1 gal/min. The filter extract and sediment collected are concentrated, slides are prepared, and the giardia cyst identified microscopically. Giardia cysts cannot be cultured. Ongerth[42] developed a procedure using a 5-μm-pore-size filter and a 10-gal sample that was reported to be efficient in recovering giardia cysts. Reservoir retention of 30 to 200 days did not reduce cyst concentration. It should be noted that whereas the giardia cyst is about 10 to 15 μm in size, the cryptosporidium oocyst is about 3 to 6 μm in size. The absence of coliform organisms does not indicate the absence of protozoa. Waterborne diseases caused by protozoa include amebic dysentery (amebiasis, *E. histolytica*), giardiasis (*G. lamblia*), cryptosporidiosis (*Cryptosporidium* spp.), meningoencephalitis (*Naegleria fowleri* and *Acanthamoeba culbertsoni*), and balantidiasis (*B. coli*.) Person-to-person contact, poor personal hygiene, and food are also common means of transmission of the diseases. Meningoencephalitis, also known as primary amebic meningoencephalitis, a rare but almost always fatal disease, is associated with swimming or bathing in warm, fresh, and brackish water. Immersion of the head (nasal passages) in the contaminated water is usually involved. The organism is commonly found in soil, fresh water, and decaying vegetation.

The helminths include roundworms, tapeworms, and flukes. The most common disease, spread by *Dracunculus medinensis* in drinking water, is dracontiasis, also known as Guinea-worm infection. Other helminths, such as *Fasciola, Schistosoma, Fasciolopsis, Echinococcus*, and *Ascaris*, are more likely to be transmitted by contaminated food and hand to mouth, particularly in areas where sanitation and personal hygiene are poor. Helminths are 50 to 60 μm in size.

Because of the resistance of the protozoa and helminths to normal chlorination and the lack of routine analytical procedures for water-treatment plant operation control, complete water treatment is required for drinking water.

Specific Pathogenic Organisms

It is not practical to routinely test for and identify specific disease organisms causing typhoid, paratyphoid, infectious hepatitis A, shigellosis, cholera, and others. (See Figure 1.2 for water treatment plant operation control.) The procedures would be too complex and time consuming for routine monitoring. However, laboratory techniques, media, and equipment are available for special studies and investigations where specific organism identification is indicated.

Physical Examinations

Odor Odor should be absent or very faint for water to be acceptable, less than 3 threshold odor number (TON). Water for food processing, beverages, and pharmaceutical manufacture should be essentially free of taste and odor. The test is very subjective, being dependent on the individual senses of smell and taste. The cause may be decaying organic matter, wastewaters including industrial wastes, dissolved gases, and chlorine in combination with certain organic compounds such as phenols. Odors are sometimes confused with tastes. The sense of smell is more sensitive than taste. Activated carbon adsorption, aeration, chemical oxidation (chlorine, chlorine dioxide, ozone, potassium permanganate), and coagulation and filtration will usually remove odors and tastes. Priority should first be given to a sanitary survey of the watershed drainage area and the removal of potential sources or causes of odors and tastes.

A technique for determining the concentration of odor compounds from a water sample to anticipate consumer complaints involves the “stripping” of odor compounds from a water sample that is adsorbed onto a carbon filter. The compounds are extracted from the filter and injected into a gas chromatograph-mass spectrometer for identification and quantification.[43]

Taste The taste of water should not be objectionable; otherwise, the consumer will resort to other sources of water that might not be of satisfactory sanitary quality. Algae, decomposing organic matter, dissolved gases, high concentrations of sulfates, chlorides, and iron, or industrial wastes may cause tastes and odors. Bone and fish oil and petroleum products such as kerosene and gasoline are particularly objectionable. Phenols in concentrations of 0.2 ppb in combination with chlorine will impart a phenolic or medicinal taste to drinking water. The taste test, like the odor test, is very subjective and may be dangerous to laboratory personnel. As in odor control, emphasis should be placed on the removal of potential causes of taste problems. See discussions of causes and methods to remove or reduce tastes and odors, later in this chapter.

Turbidity Turbidity is due to suspended material such as clay, silt, or organic and inorganic materials. Enhanced surface-water regulations in the United States require that the maximum contaminant level for turbidity not exceed 0.5 NTU in 95 percent of the samples taken every month and must never exceed 1 NTU. Additionally, the utility must maintain a minimum of 0.2 mg/1 free chlorine residual at representative points within the distribution system. Turbidity measurements are made in terms of nephelometric turbidity units (NTU), Formazin turbidity units (FTU), and Jackson turbidity units (JTU). The lowest turbidity value that can be measured directly on the Jackson candle turbidimeter is 25 units. There is no direct relationship between NTU or FTU readings and JTU readings.[44] The NTU is the standard measure, requiring use of a nephelometer, which measures the amount of light scattered, usually at 90° from the light direction, by suspended particles in the water test sample. It can measure turbidities of less than 1 unit and differences of 0.02 unit. Secondary turbidity measurement standards calibrated against the Formazin standard may also be accepted by the EPA.

The public demands sparkling clear water. This implies a turbidity of less than 1 unit; a level of less than 0.1 unit, which is obtainable when water is coagulated, flocculated, settled, and filtered, is practical. Turbidity is a good measure of sedimentation, filtration, and storage efficiency, particularly if supplemented by the total microscopic and particle count. Increased chlorine residual, bacteriological sampling, and main flushing is indicated when the maximum contaminant level for turbidity is exceeded in the distribution system until the cause is determined and eliminated. Turbidity will interfere with proper disinfection of water, harbor microorganisms, and cause tastes and odors. As turbidity increases, coliform masking in the membrane filter technique is increased.

The American Water Works Association recommends an operating level of no more than 0.3 NTU in filter plant effluent and a goal of no more than 0.2 NTU.

An increase in the turbidity of well water after heavy rains may indicate the entrance of inadequately purified groundwater.

Color Color should be less than 15 true color units* (sample is first filtered), although persons accustomed to clear water may notice a color of only 5 units. The goal is less than 3 units. Water for industrial uses should generally have a color of 5 to 10 or less. Color is caused by substances in solution, known as true color, and by substances in suspension, mostly organics causing apparent or organic color. Iron, copper, manganese, and industrial wastes may also cause color.

Water that has drained through peat bogs, swamps, forests, or decomposing organic matter may contain a brownish or reddish stain due to tannates and organic acids dissolved from leaves, bark, and plants. Excessive growths of algae or microorganisms may also cause color.

Color resulting from the presence of organics in water may also cause taste, interfere with chlorination, induce bacterial growth, make water unusable by certain industries without further treatment, foul anion exchange resins, interfere with colorimetric measurements, limit aquatic productivity by absorbing photosynthetic light, render lead in pipes soluble, hold iron and manganese in solution causing color and staining of laundry and plumbing fixtures, and interfere with chemical coagulation. Chlorination of natural waters containing organic water color (and humic acid) results in the formation of trihalomethanes, including chloroform. This is discussed later.

Color can be controlled at the source by watershed management. Involved is identifying waters from sources contributing natural organic and inorganic

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*Cobalt platinum units.

color and excluding them, controlling beaver populations, increasing water flow gradients, using settling basins at inlets to reservoirs, and blending water.[45] Coagulation, flocculation, settling, and rapid sand filtration should reduce color-causing substances in solution to less than 5 units, with coagulation as the major factor. Slow sand filters should remove about 40 percent of the total color. True color is costly to remove. Oxidation (chlorine, ozone) or carbon adsorption also reduces color.

Temperature The water temperature should preferably be less than 60°F (16°C). Groundwaters and surface waters from mountainous areas are generally in the temperature range of 50° to 60°F (10°–16°C). Design and construction of water systems should provide for burying or covering of transmission mains to keep drinking water cool and prevent freezing in cold climates or leaks due to vehicular traffic. High water temperatures accelerate the growth of nuisance organisms, and taste and odor problems are intensified. Low temperatures somewhat decrease the disinfection efficiency.

Microscopic Examination

Microscopic and macroscopic organisms that may be found in drinking water sources include bacteria, algae, actinomycetes, protozoa, rotifers, yeasts, molds, small crustacea, worms, and mites. Most algae contain chlorophyll and require sunlight for their growth. The small worms are usually insect larvae. Larvae, crustacea, worms, molds or fungi, large numbers of algae, or filamentous growths in the drinking water would make the water aesthetically unacceptable and affect taste and odor. Immediate investigation to eliminate the cause would be indicated.

The term *plankton* includes algae and small animals such as cyclops and daphnia. Plankton are microscopic plants and animals suspended and floating in fresh and salt water and are a major source of food for fish. Algae include diatoms, cyanophyceae or blue-green algae (bacteria), and chlorophyceae or green algae; they are also referred to as phytoplankton. Protozoan and other small animals are referred to as zooplankton. They feed on algae and bacteria. The microbial flora in bottom sediments are called the benthos.[46] Phototrophic microorganisms are plankton primarily responsible for the production of organic matter via photosynthesis.

Algal growths increase the organic load in water, excrete oils that produce tastes and odors, clog sand filters, clog intake screens, produce slimes, interfere with recreational use of water, may cause fish kills when in "bloom" and in large surface "mats" by preventing replenishment of oxygen in the water, become attached to reservoir walls, form slimes in open reservoirs and recirculating systems, and contribute to corrosion in open steel tanks[47] and disintegration of concrete. Algae increase oxygen, and heavy concentrations reduce hardness and salts. In the absence of carbon dioxide, algae break down bicarbonates to carbonates, thereby raising the water pH to 9 or higher. Algae also contribute organics, which on chlorination add to trihalomethane formation.

Microscopic examination involves collection of water samples from specified locations and depths. The sample is preserved by the addition of formaldehyde if not taken immediately to the laboratory. At the laboratory, the plankton in the sample is concentrated by means of a centrifuge or a Sedgwick–Rafter sand filter. A 1-ml sample of the concentrate is then placed in a Sedgwick-Rafter counting cell for enumeration using a compound microscope fitted with a Whipple ocular micrometer. The Lackey Drop Microtransect Counting Method is also used, particularly with samples containing dense plankton populations.[48] Enumeration methods include total cell count, clump count, and areal standard unit count.

Examinations of surface-water sources, water mains, and well-water supplies, which are sources of difficulty, should be made weekly to observe trends and determine the need for treatment or other controls and their effectiveness before the organisms reach nuisance proportions. The "areal standard unit" represents an area 20 microns (μm) square or 400 μm^2. One micrometer equals 0.001 mm. Microorganisms are reported as the number of areal standard units per milliliter. Protozoa, rotifers, and other animal life are individually counted. Material that cannot be identified is reported as areal standard units of amorphous matter (detritus). The apparatus, procedure, and calculation of results and conversion to "Cubic Standard Units" is explained in *Standard Methods*.[49]

When more than 300 areal standard units, or organisms, per milliliter is reported, treatment with $CuSO_4$ is indicated to prevent possible trouble with tastes and odors or short filter runs. When more than 500 areal standard units or cells per milliliter is reported, complaints can be expected and the need for immediate action is indicated. A thousand units or more of amorphous matter indicates probable heavy growth of organisms that have died and disintegrated or organic debris from decaying algae, leaves, and similar materials.

The presence of asterionella, tabellaria, synedra, beggiatoa, crenothrix, *Sphaerotilis natans*, mallomonas, anabaena, aphanizomenon, volvox, ceratium, dinobryon, synura, uroglenopsis, and others, some even in small concentrations, may cause tastes and odors that are aggravated where marginal chlorine treatment is used. Free residual chlorination will usually reduce the tastes and odors. More than 25 areal standard units per milliliter of synura, dinobryon, or uroglena, or 300 to 700 units of asterionella, dictyosphaerium, aphanizomenon, volvox, or ceratium in chlorinated water will usually cause taste and odor complaints. The appearance of even 1 areal standard unit of a microorganism may be an indication to start immediate copper sulfate treatment if past experience indicates that trouble can be expected.

The blue-green algae, anabaena, microcystis (polycystis), nodularia, gloeotrichia, coelosphaerium, *Nostoc rivulare*, and aphanizomenon in large concentrations have been responsible for killing fish and causing illness in horses, sheep, dogs, ducks, chickens, mice, and cattle.[50] Illness in humans from these causes has been suspected, but confirmatory evidence is limited.[51] Gorham[52] estimated that the oral minimum lethal dose of decomposing toxic microcystis bloom for a 150-lb man is 1 to 2 quarts of thick, paintlike suspension and concluded that toxic waterblooms of blue-green algae in public water supplies are not a significant health hazard. Red tides caused by the dinoflagellates *Gonyaulax monilata* and *Gymnodinium brevis* have been correlated with mass mortality of fish.[53] Coagulation, flocculation, sedimentation, and filtration do not remove algal toxins, nor does the usual activated carbon treatment.

Investigation of conditions contributing to or favoring the growth of plankton in a reservoir and their control should reduce dependence on copper sulfate treatment. See "Control of Microorganisms", in Chapter 2.

Chemical Examinations*

The significance of selected chemical elements and compounds in drinking water is discussed next. An intake of 2 liters of water per day per person is assumed in determining health effects. The MCL is the National Drinking Water Regulation maximum contaminant level. The maximum contaminant level goal (MCLG) is a desirable one and is nonmandatory unless specifically made so by a state. The WHO level represents a guideline value "of a constituent that ensures an aesthetically pleasing water and does not result in any significant risk to the health of the consumer."[54] A value in excess of the guideline value does not in itself imply that the water is unsuitable for consumption. A comprehensive discussion of health-related inorganic and organic constituents can be found in *Guidelines for Drinking-Water Quality*, Vol. 2, WHO, Geneva, 1984.[55] Gas chromatographic mass spectrometry is considered the best method for identifying and quantifying specific organic compounds in an unknown sample. The removal of organic and inorganic chemicals from drinking water is reviewed later in this chapter.

Albuminoid Ammonia Albuminoid ammonia represents "complex" organic matter and thus would be present in relatively high concentrations in water-supporting algae growth, receiving forest drainage, or containing other organic matter. Concentrations of albuminoid ammonia higher than about 0.15 mg/1, therefore, should be appraised in the light of origin of the water and the results of microscopic examination. In general, the following concentrations serve as a guide: low—less than 0.06 mg/1; moderate—0.06 to 0.15 mg/1; high—0.15 mg/1 or greater. When organic nitrogen and ammonia nitrogen forms are found together, they are measured as Kjeldahl nitrogen.

Alkalinity The alkalinity of water passing through distribution systems with iron pipe should be in the range of 30 to 100 mg/1, as $CaCO_3$, to prevent serious corrosion; up to 500 mg/1 is acceptable, although this factor must be appraised from the standpoint of pH, hardness, carbon dioxide, and dissolved-oxygen content. Corrosion of iron pipe is prevented by the maintenance of calcium carbonate stability. Undersaturation will result in corrosive action in iron water mains and

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*Results are reported as milligrams per liter (mg/1), which for all practical purposes can be taken to be the same as parts per million (ppm), except when the concentrations of substances in solution approach or exceed 7000 mg/1, when a density correction should be made.

cause red water. Oversaturation will result in carbonate deposition in piping and water heaters and on utensils. See "Corrosion Cause and Control", in Chapter 2. Potassium carbonate, potassium bicarbonate, sodium carbonate, sodium bicarbonate, phosphates, and hydroxides cause alkalinity in natural water. Calcium carbonate, calcium bicarbonate, magnesium carbonate, and magnesium bicarbonate cause hardness, as well as alkalinity. Sufficient alkalinity is needed in water to react with added alum to form a floc in water coagulation. Insufficient alkalinity will cause alum to remain in solution. Bathing or washing in water of excessive alkalinity can change the pH of the lacrimal fluid around the eye, causing eye irritation.

Aluminum The EPA-recommended goal is less than 0.05 mg/1; the WHO guideline is 0.2 mg/1.[56] Aluminum is not found naturally in the elemental form, although it is one of the most abundant metals on the earth's surface. It is found in all soils, plants, and animal tissues. Aluminum-containing wastes concentrate in and can harm shellfish and bottom life.[57] Alum as aluminum sulfate is commonly used as a coagulant in water treatment; excessive aluminum may pass through the filter with improper pH control. Precipitation may take place in the distribution system or on standing when the water contains more than 0.5 mg/1. Its presence in filter plant effluent is used as a measure of filtration efficiency. Although ingested aluminum does not appear to be harmful, aluminum compounds have been associated with neurological disorders in persons on kidney dialysis machines. Aluminum in the presence of iron may cause water discoloration. There may be an association between aluminum and Alzheimer's disease, but this has not been confirmed.[58]

Arsenic The MCL for arsenic in drinking water was lowered from 0.05 mg/1 to 0.01 mg/1 by the EPA in January 2001. The WHO guideline is also 0.01 mg/1. (The Occupational Safety and Health Administration (OSHA) standard is 10 $\mu g/m^3$ for occupational exposure to inorganic arsenic in air over an 8-hour day; 2 $\mu g/m^3$ for 24 hour exposure to ambient air.[59]) A probable lethal oral dose is 5 to 20 mg/kg, depending on the compound and individual sensitivity. Sources of arsenic are natural rock formations (phosphate rock), industrial wastes, arsenic pesticides, fertilizers, detergent "presoaks," and possibly other detergents. It is also found in foods, including shellfish and tobacco, and in the air in some locations.

There is ample evidence that defines a relationship between certain cancers (e.g., skin, bladder, kidney, lung, liver) and high levels of arsenic in drinking water (i.e., above 0.2 mg/1). There is significant debate, however, if these cancers are seen at lower levels of arsenic. Arsenic occurs naturally as arsenic, +3 (arsenite) and arsenic, +5 (arsenate). Arsenites are more toxic than arsenates. Arsenic may be converted to dimethylarsine by anaerobic organisms and accumulate in fish, similar to methylmercury.[60] After many years of scientific research and debate, the USEPA concluded that a concentration of 10 $\mu g/1$ (0.01 mg/1) is protective of public health. Promulgated in 2001, the lowered MCL required over 3,000 public water systems to install removal systems (or blend or abandon the high arsenic wells) by the Rule deadline of February 2006. For treatment, see “Removal of Inorganic Chemicals”, in Chapter 2.

Asbestos Most asbestos-related diseases (mesotheliomas) are associated with the breathing of air containing asbestos fibers as long as 20 years earlier. Sources of exposure include working or living in the immediate vicinity of crocidolite mines, asbestos insulation and textile factories, and shipyards. Asbestos in drinking water may come from certain naturally occurring silicate materials in contact with water or from eroded asbestos cement pipe. A study (1935–1973) on the incidence of gastrointestinal cancer and use of drinking water distributed through asbestos cement (A/C) pipe reached the preliminary conclusion that “no association was noted between these asbestos risk sources and gastrointestinal tumor incidence.”[61] A subsequent study concluded, “The lack of coherent evidence for cancer risk from the use of A/C pipe is reassuring.”[62] An EPA study shows no statistical association between deaths due to certain types of cancer and the use of A/C pipe. British researchers reported that the cancer risk was “sensibly zero” or exceedingly low[63]: “Available studies on humans and animals do not provide evidence to support the view that ingestion of drinking water containing asbestos causes organ-specific cancers.” Nevertheless, exposure to the asbestos fibers in drinking water should be reduced. Conventional water treatment, including coagulation and filtration, will remove more than 90 percent of the asbestos fibers in the raw water.[64]

Asbestos cement pipe was found to behave much like other piping materials, except polyvinyl chloride (PVC), that are commonly used for the distribution of drinking water. It has been concluded that, where “aggressive water conditions exist, the pipe will corrode and deteriorate; if aggressive water conditions do not exist, the pipe will not corrode and deteriorate.”[65] Aggressive water can leach calcium hydroxide from the cement in A/C pipe. The American Water Works Association (AWWA) Standard C400-77 establishes criteria for the type of pipe to use for nonaggressive water (≥ 12.0), moderately aggressive water (10.9–11.9), and highly aggressive water (≤ 10.0), based on the sum of the pH plus the log of the alkalinity times the calcium hardness, as calcium carbonate. Remedial measures, in addition to pH adjustment and control of corrosion, include chemical addition to build up a protective film, elimination of hydrogen sulfide, rehabilitation and lining of existing pipe, pipe replacement, and a flushing program. Asbestos cement pipe should not be used to carry aggressive water.

If the water is heavily contaminated, its use for humidifiers, showers, food preparation, clothes laundering, and drinking is not advised since the asbestos fibers can become airborne and be inhaled. The EPA has recommended a maximum contaminant level of 7.1×10^6 asbestos fibers longer than 10 μm/1 from all sources, including naturally occurring asbestos. On July 6, 1989, the EPA ruled to prohibit manufacture, importation, and processing of asbestos in certain products and to phase out the use of asbestos in all other products. This action was meant to reduce airborne asbestos in the workplace and ambient air and thereby the carcinogenic health risk associated with the inhalation of asbestos fibers.

Barium Barium may be found naturally in groundwater (usually in concentrations less than 0.1 mg/1) and in surface water receiving industrial wastes; it is also found in air. It is a muscle stimulant and in large quantities may be harmful to the nervous system and heart. The fatal dose is 550 to 600 mg. The MCL is 2 mg/1 in drinking water. A WHO guideline has not been established; concentrations of 10 mg/1 are not considered significant. Barium can be removed by weak-acid ion exchange.

Benzene This chemical is used as a solvent and degreaser of metals.[66] It is also a major component of gasoline. Drinking water contamination generally results from leaking underground gasoline and petroleum tanks or improper waste disposal. Benzene has been associated with significantly increased risks of leukemia among certain industrial workers exposed to relatively large amounts of this chemical during their working careers. This chemical has also been shown to cause cancer in laboratory animals when the animals are exposed to high levels over their lifetimes. Chemicals that cause increased risk of cancer among exposed industrial workers and in laboratory animals also may increase the risk of cancer in humans who are exposed at lower levels over long periods of time. The EPA has set the enforceable drinking water standard for benzene at 0.005 mg/1 to reduce the risk of cancer or other adverse health effects observed in humans and laboratory animals. The OSHA standard is 1 mg/1 with 5 mg/1 for short-term (15-minutes) exposure.[67]

Cadmium The federal drinking water MCL for cadmium is 0.005 mg/1. The WHO guideline is 0.005 mg/1.[68] Common sources of cadmium are water mains and galvanized iron pipes, tanks, metal roofs where cistern water is collected, industrial wastes (electroplating), tailings, pesticides, nickel plating, solder, incandescent light filaments, photography wastes, paints, plastics, inks, nickel–cadmium batteries, and cadmium-plated utensils. It is also found in zinc and lead ores. Cadmium vaporizes when burned; salts of cadmium readily dissolve in water and can, therefore, be found in air pollutants, wastewater, wastewater sludge, fertilizer, land runoff, some food crops, tobacco, and drinking water. Beef liver and shellfish are very high in cadmium. Large concentrations may be related to kidney damage, hypertension (high blood pressure), chronic bronchitis, and emphysema. Cadmium builds up in the human body, plants, and food animals. It has a biological half-life of about 20 years.[69] The direct relationship between cardiovascular death rates in the United States, Great Britain, Sweden, Canada, and Japan and the degree of softness or acidity of water point to cadmium as the suspect.[70] In 1972, the Joint WHO Food and Agriculture Organization Expert Committee on Food Additives established a provisional tolerable weekly cadmium intake of 400 to 500 μg. Cadmium removal from water is discussed in Chapter 2.

Carbon–Chloroform Extract (CCE) and Carbon–Alcohol Extract (CAE) (Tests No Longer Routinely Used) Carbon–chloroform extract may include chlorinated hydrocarbon pesticides, nitrates, nitrobenzenes, aromatic ethers, and many others adsorbed on an activated carbon cartridge. Water from uninhabited and nonindustrial watersheds usually show CCE concentrations of less than 0.04 mg/1. The taste and odor of drinking water can be expected to be poor when the concentration of CCE reaches 0.2 mg/1. Carbon–alcohol extract measures gross organic chemicals including synthetics. A goal of less than 0.04 mg/1 CCE and 0.10 mg/1 CAE has been proposed.

Carbon Dioxide The only limitation on carbon dioxide is that pertaining to corrosion. It should be less than 10 mg/1, but when the alkalinity is less than 100 mg/1, the CO_2 concentration should not exceed 5.0 mg/1.

Carbon Tetrachloride This chemical was once a popular household cleaning fluid.[71] It generally gets into drinking water by improper disposal. This chemical has been shown to cause cancer in laboratory animals such as rats and mice when exposed at high levels over their lifetimes. Chemicals that cause cancer in laboratory animals may also increase the risk of cancer in humans exposed at lower levels over long periods of time. The EPA has set the enforceable drinking water standard for carbon tetrachloride at 0.005 mg/1 to reduce the risk of cancer or other adverse health effects observed in laboratory animals. The WHO *tentative* guideline value is 3 μg/1.

Chlorides of Intestinal Origin Natural waters remote from the influence of ocean or salt deposits and not influenced by local sources of pollution have a low chloride content, usually less than 4.0 mg/1. Due to the extensive salt deposits in certain parts of the country, it is impractical to assign chloride concentrations that, when exceeded, indicate the presence of sewage, agricultural, or industrial pollution, unless a chloride record over an extended period of time is kept on each water supply. In view of the fact that chlorides are soluble, they will pass through pervious soil and rock for great distances without diminution in concentration, and thus the chloride content must be interpreted with considerable discretion in connection with other constituents in the water. The concentration of chlorides in urine is about 5000 mg/1, in septic tank effluent about 80 mg/1, and in sewage from a residential community 50 mg/1 depending on the water source.

Chlorides of Mineral Origin The WHO guideline for chloride ion is 250 mg/1.[72] A goal of less than 100 mg/1 is recommended. The permissible chloride content of water depends on the sensitivity of the consumer. Many people notice a brackish taste imparted by 125 mg/1 of chlorides in combination with sodium, potassium, or calcium, whereas others are satisfied with concentrations as high as 250 mg/1. Irrigation waters should contain less than 200 mg/1. When the chloride is in the form of sodium chloride, use of the water for drinking may be inadvisable for persons who are under medical care for certain forms of heart disease. The main intake of chlorides is with foods. Hard water softened by the ion exchange or lime-soda process (with Na_2CO_3) will increase sodium concentrations in the water. Salt used for highway deicing may contaminate groundwater and surface-water supplies. Its use should be curtailed and storage depots covered. Chlorides can be removed from water by distillation, reverse osmosis, or electrodialysis and minimized by proper aquifer selection and well construction. Water sources near oceans or in the vicinity of underground salt deposits may contain high salt concentrations. Well waters from sedimentary rock are likely to contain chlorides. The corrosivity of water is increased by high concentrations of chlorides, particularly if the water has a low alkalinity.

Chromium The total chromium MCL and WHO guideline[73] is 0.1 mg/1 in drinking water. Chromium is found in cigarettes, some foods, the air, and industrial plating, paint, and leather tanning wastes. Chromium deficiency is associated with atherosclerosis. Hexavalent chromium dust can cause cancer of the lungs and kidney damage.[74]

Copper The EPA action level for copper is 1.3 mg/1; the WHO guideline is 1.0 mg/1.[75] The goal is less than 0.2 mg/1. Concentrations of this magnitude are not present in natural waters but may be due to the corrosion of copper or brass piping; 0.5 to 1.0 mg/1 in soft water stains laundry and plumbing fixtures blue–green. A concentration in excess of 0.2 to 0.3 mg/1 will cause an "off" flavor in coffee and tea; 5 mg/1 or less results in a bitter metallic taste; 1 mg/1 may affect film and reacts with soap to produce a green color in water; 0.25 to 1.0 mg/1 is toxic to fish. Corrosion of galvanized iron and steel fittings is reported to be enhanced by copper in public water supplies. Copper appears to be essential for all forms of life, but excessive amounts are toxic to fish. The estimated adult daily requirement is 2.0 mg, coming mostly from food. Copper deficiency is associated with anemia. Copper salts are commonly used to control algal growths in reservoirs and slime growths in water systems. Copper can be removed by ion exchange, conventional coagulation, sedimentation, filtration, softening, or reverse osmosis; when caused by corrosion of copper pipes, it can be controlled by proper water treatment and pH control. Copper sulfate treatment of the water source for algae control may contribute copper to the finished water. Electrical grounding to copper water pipe can add to the copper dissolution.

Corrosivity Water should be noncorrosive. Corrosivity of water is related to its pH, alkalinity, hardness, temperature, dissolved oxygen, carbon dioxide, total dissolved solids, and other factors. Waters high in chlorides and low in alkalinity are particularly corrosive. Since a simple, rapid test for corrosivity is not available, test pipe sections or metal coupons (90-day test) are used, supplemented, where possible, by water analyses such as calcium carbonate saturation, alkalinity, pH, and dissolved solids and gases. Incrustation on stainless steel test pipe or metal coupon should not exceed 0.05 mg/cm^2; loss by corrosion of galvanized iron should not exceed 5.00 mg/cm^2 (AWWA). The corrosion of copper tubing increases particularly when carrying water above 140°F (60°C). Schroeder[76] reports that pewter, britannia metal, water pipes, and cisterns may contain antimony, lead, cadmium, and tin, which leach out in the presence of soft water or acidic fluids. Soft water flowing over galvanized iron roofs or through galvanized iron pipes or stored in galvanized tanks contains cadmium and zinc. Ceramic vessels contain antimony, beryllium, barium, nickel, and zirconium; pottery glazes contain lead, all of which may be leached out if improper firing and glazing are used. Corrosivity is controlled by pH, alkalinity, and calcium carbonate adjustment, including use of lime, sodium carbonate, and/or sodium hydroxide. Other means include the addition of polyphosphate, orthophosphate, and silicates and pH control. In any case, corrosion-resistant pipe should be used where possible.

Cyanide Cyanide is found naturally and in industrial wastes. Cyanide concentrations as low as 10 μg/1 have been reported to cause adverse effects in fish. Long-term consumption of up to 4.7 mg/day has shown no injurious effects (ref. 45, pp. 128–136). The cyanide concentration in drinking water should not exceed 0.2 mg/1. The probable oral lethal dose is 1.0 mg/kg. The WHO guideline is 0.1 mg/1. An MCL and MCLG of 0.2 mg/1 has been established by the EPA. Cyanates can ultimately decompose to carbon dioxide and nitrogen gas.[77] Cyanide is readily destroyed by conventional treatment processes.

1,1-Dichloroethylene This chemical is used in industry and is found in drinking water as a result of the breakdown of related solvents.[78] The solvents are used as cleaners and degreasers of metals and generally get into drinking water by improper waste disposal. This chemical has been shown to cause liver and kidney damage in laboratory animals such as rats and mice when exposed at high levels over their lifetimes. Chemicals that cause adverse effects in laboratory animals may also cause adverse health effects in humans exposed at lower levels over long periods of time. The EPA has set the enforceable drinking water standard for 1,1-dichloroethylene at 0.007 mg/1 to reduce the risk of the adverse health effects observed in laboratory animals.

1,2-Dichloroethane This chemical is used as a cleaning fluid for fats, oils, waxes, and resins.[79] It generally gets into drinking water from improper waste disposal. This chemical has been shown to cause cancer in laboratory animals such as rats and mice when exposed at high levels over their lifetimes. Chemicals that cause cancer in laboratory animals may also increase the risk of cancer in humans exposed at lower levels over long periods of time. The EPA has set the enforceable drinking water standard for 1,2-dichloroethane at 0.005 mg/1 to reduce the risk of cancer or other adverse health effects observed in laboratory animals. The WHO guideline is 10 μg/1.

Dissolved Oxygen Water devoid of dissolved oxygen frequently has a “flat” taste, although many attractive well waters are devoid of oxygen. In general, it is preferable for the dissolved-oxygen content to exceed 2.5 to 3.0 mg/1 to prevent secondary tastes and odors from developing and to support fish life. Game fish require a dissolved oxygen of at least 5.0 mg/1 to reproduce and either die off or migrate when the dissolved oxygen falls below 3.0 mg/1. The concentration of dissolved oxygen in potable water may be related to problems associated with iron, manganese, copper, and nitrogen and sulfur compounds.

Fluorides Fluorides are found in many groundwaters as a natural constituent, ranging from a trace to 5 mg/1 or more, and in some foods. Fluorides in concentrations greater than 4 mg/1 can cause the teeth of children to become mottled and discolored, depending on the concentration and amount of water consumed. Mottling of teeth has been reported very occasionally above 1.5 mg/1 according to WHO guidelines. Drinking water containing 0.7 to 1.2 mg/1 natural or added fluoride is beneficial to children during the time they are developing permanent teeth. An optimum level is 1.0 mg/1 in temperate climates. The Centers for Disease Control and Prevention (CDC) estimates that in 2006, approximately 69.2 percent of the United States' population (or 184 million people) had access to optimum levels of fluoridated water (0.7 mg/1 to 1.2 mg/l). More than 65 percent of the nation's nine-year-old children are free of tooth decay and the CDC also considers fluoridation of community water systems one of the 10 great public health achievements of the 20th century.[80]

The maximum contaminant level in drinking water has been established in the National Drinking Water Regulations at 4 mg/1. The probable oral lethal dose for sodium fluoride is 70 to 140 mg/kg. Fluoride removal methods include reverse osmosis, lime softening, ion exchange using bone char or activated alumina, and tricalcium phosphate adsorption. It is not possible to reduce the fluoride level to 1 mg/1 using only lime.[81] The WHO and CDC reports show no evidence to support any association between fluoridation of drinking water and the occurrence of cancer (1982).

Free Ammonia Free ammonia represents the first product of the decomposition of organic matter; thus, appreciable concentrations of free ammonia usually indicate "fresh pollution" of sanitary significance. The exception is when ammonium sulfate of mineral origin is involved. The following values may be of general significance in appraising free ammonia content in groundwater: low—0.015 to 0.03 mg/1; moderate—0.03 to 0.10 mg/1; high—0.10 mg/1 or greater. In treated drinking water, the goal is less than 0.1 mg/1, but less than 0.5 mg/1 is acceptable. Special care must be exercised to allow for ammonia added if the "chlorine–ammonia" treatment of water is used or if crenothrix organisms are present. If ammonia is present or added, chloramines are formed when chlorine is added to the water. Ammonia in the range of 0.2 to 2.0 mg/1 is toxic to many fish. A recommended maximum is 0.5 mg/1 to 0.2 mg/1 for rainbow trout. Chloramines are also toxic to other aquatic life. Ammonia serves as a plant nutrient, accelerating eutrophication in receiving waters. It is converted to nitrite and then to nitrate, first by *Nitrosomonas* and then by *Nitrobacter* organisms. Ammonia can be removed by breakpoint or superchlorination.

Hardness Hardness is due primarily to calcium and secondarily to magnesium carbonates and bicarbonates (carbonate or temporary hardness that can be removed by heating) and calcium sulfate, calcium chloride, magnesium sulfate, and magnesium chloride (noncarbonate or permanent hardness, which cannot be removed by heating); the sum is the total hardness expressed as calcium carbonate. In general, water softer than 50 mg/1, as $CaCO_3$ is corrosive, whereas waters harder than about 80 mg/1 lead to the use of more soap and above 200 mg/1 may cause incrustation in pipes. Lead, cadmium, zinc, and copper in solution are usually caused by pipe corrosion associated with soft water. Desirable hardness values, therefore, should be 50 to 80 mg/1, with 80 to 150 mg/1 as passable, over 150 mg/1 as undesirable, and greater than 500 as unacceptable. The U.S. Geological Survey (USGS) and WHO[82] classify hardness, in milligrams per liter as $CaCO_3$, as 0 to 60 soft, 61 to 120 moderately hard, 121 to 180 hard, and more than 180 very hard. Waters high in sulfates (above 600 to 800 mg/1 calcium sulfate, 300 mg/1 sodium sulfate, or 390 mg/1 magnesium sulfate) are laxative to those not accustomed to the water. Depending on alkalinity, pH, and other factors, hardness above 200 mg/1 may cause the buildup of scale and flow reduction in pipes. In addition to being objectionable for laundry and other washing purposes due to soap curdling, excessive hardness contributes to the deterioration of fabrics. Hard water is not suitable for the production of ice, soft drinks, felts, or textiles. Satisfactory cleansing of laundry, dishes, and utensils is made difficult or impractical. When heated, bicarbonates precipitate as carbonates and adhere to the pipe or vessel. In boiler and hot-water tanks, the scale resulting from hardness reduces the thermal efficiency and eventually causes restriction of the flow or plugging in the pipes. Calcium chloride, when heated, becomes acidic and pits boiler tubes. Hardness can be reduced by lime-soda ash chemical treatment or the ion exchange process, but the sodium concentration will be increased. See “Water Softening,” in Chapter 2. Desalination will also remove water hardness.

There seem to be higher mortality rates from cardiovascular diseases in people provided with soft water than in those provided with hard water. Water softened by the ion exchange process increases the sodium content of the finished water. The high concentration of sodium and the low concentration of magnesium have been implicated, but low concentrations of chromium and high concentrations of copper have also been suggested as being responsible. High concentrations of cadmium are believed to be associated with hypertension. Cause and effect for any of these is not firm.

Hydrogen Sulfide Hydrogen sulfide is most frequently found in groundwaters as a natural constituent and is easily identified by a rotten-egg odor. It is caused by microbial action on organic matter or the reduction of sulfate ions to sulfide. A concentration of 70 mg/1 is an irritant, but 700 mg/1 is highly poisonous. In high concentration, it paralyzes the sense of smell, thereby making it more dangerous. Black stains on laundered clothes and black deposits in piping and on plumbing fixtures are caused by hydrogen sulfide in the presence of soluble iron. Hydrogen sulfide in drinking water should not be detectable by smell or exceed 0.05 mg/1. Hydrogen sulfide predominates at pH of 7.0 or less. It is removed by aeration or chemical oxidation followed by filtration.

Iron Iron is found naturally in groundwaters and in some surface waters and as the result of corrosion of iron pipe. Iron deposits and mining operations and distribution systems may be a source of iron and manganese. Water should have a soluble iron content of less than 0.1 mg/1 to prevent reddish-brown staining of laundry, fountains, and plumbing fixtures and to prevent pipe deposits. The secondary MCL and WHO guideline level is 0.3 mg/1; the goal should be less than 0.05 mg/1. Some staining of plumbing fixtures may occur at 0.05 mg/1. Precipitated ferric hydroxide may cause a slight turbidity in water that can be objectionable and cause clogging of filters and softener resin beds. In combination with manganese, concentrations in excess of 0.3 mg/1 cause complaints. Precipitated iron may cause some turbidity. Iron in excess of 1.0 mg/1 will cause an unpleasant taste. A concentration of about 1 mg/1 is noticeable in the taste of coffee or tea. Conventional water treatment or ion exchange will remove iron. Chlorine or oxygen will precipitate soluble iron. Iron is an essential element for human health. See "Iron and Manganese Occurrence and Removal," in Chapter 2.

Lead The EPA requires that when more than 10 percent of tap water samples exceed 15 μg/1, the utility must institute corrosion control treatment. Concentrations exceeding this value occur when corrosive waters of low mineral content and softened waters are piped through lead pipe and old lead house services. Zinc-galvanized iron pipe, copper pipe with lead-based solder joints, and brass pipe, faucets, and fittings may also contribute lead. The lead should not exceed 5 μg/1 in the distribution system.

Lead, as well as cadmium, zinc, and copper, is dissolved by carbonated beverages, which are highly charged with carbon dioxide. Limestone, galena, water, and food are natural sources of lead. Other sources are motor vehicle exhaust, certain industrial wastes, mines and smelters, lead paints, glazes, car battery salvage operations, soil, dust, tobacco, cosmetics, and agricultural sprays. Fallout from airborne pollutants also contributes significant concentrations of lead to water supply reservoirs and drainage basins. About one-fifth of the lead ingested in water is absorbed. The EPA estimates that in young children about 20 percent of lead exposure comes from drinking water; dust contributes at least 30 percent, air 5 to 20 percent, and food 30 to 45 percent.[83]

The Safe Drinking Water Amendments of 1986 require that any pipe, solder, or flux used in the installation or repair of any public water system or any plumbing connected to a public water system shall be lead free. Acceptable substitutes for lead solder are tin–silver, tin–antimony, and tin–copper. Solder and flux containing not more than 0.2 percent lead and pipes and pipe fittings containing not more than 8.0 percent lead are considered to be lead free. Lead-free solder may contain trace amounts of lead, tin, silver, and copper. (Leaded joints necessary for the repair of cast-iron water mains are excluded from the prohibition.) Exposure to lead in tap water is more likely in new homes, less than 5 years old, where plumbing contains lead solder or flux. A survey by the AWWA showed an average lead concentration of 193.3 μg/1 in first-draw samples from homes less than 2 years old, 45.7 μg/1 from homes 2 to 5 years old, 16 μg/1 from homes 5 to 10 years old, and 8.2 μg/1 from homes older than 10 years.[84] Hot water would normally contain higher concentrations of lead. Lead flux is reported to dissolve at about 140° to 150°F (60°–66°C). Hot-water flushing is an economical method for removing residual flux from piping in newer buildings.[85] Galvanic corrosion due to dissimilar metals—copper and lead–tin solder—will also contribute lead. Electric water cooler piping, water contact surfaces, and fittings have also been implicated as sources of lead in drinking water. Defective coolers are being replaced.

Water containing lead in excess of the standard should not be used for baby formula or for cooking or drinking. Flushing the standing water out of a faucet for about 1 minute will minimize the lead concentration, but it does not solve the problem. The Secretary of Housing and Urban Development and the Administrator of the Veterans' Administration may not ensure or guarantee a mortgage or furnish assistance with respect to newly constructed residential property, which contains a potable water system, unless such system uses only lead-free pipe, solder, and flux.

The EPA requires the following measures and standards to control lead in community and noncommunity nontransient water systems:

1. Corrosion control when tap water sample average exceeds 0.01 mg/1, when the pH level is less than 8.0 in more than 5 percent of samples, and when the copper level exceeds 1.3 mg/1 (pH not greater than 9.0, alkalinity of 25–100 mg/1 as calcium carbonate)
2. An MCL for lead of 0.005 mg/1 and a MCLG of zero leaving the treatment plant
3. An MCL and an MCLG for copper of 1.3 mg/1
4. Tap water lead "action level" of 0.015 mg/1 in not more than 10 percent of samples of tap water that has been allowed to stand at least 6 hours (usually the first draw in the morning) from dwelling units that contain copper pipes with lead solder installed after 1982

Water treatment or use of a corrosion inhibitor is advised where indicated. Conventional water treatment, including coagulation, will partially remove natural or manmade lead in raw water. Measures to prevent or minimize lead dissolution include maintenance of pH $\geq$ 8.0 and use of zinc orthophosphate or polyphosphates. Silicates may have a long-term beneficial effect. No apparent relationship was found between lead solubility and free chlorine residual, hardness, or calcium level. Electrical grounding to plumbing increased lead levels. Alkalinity level control was not of value at pH 7.0 to $<$8.0.[86] However, since only 3 to 5 percent of the free chlorine is in the active hypochlorous acid form at pH 9.0, whereas 23 to 32 percent is in the hypochlorous acid form at pH 8.0, pH level control is critical for corrosion control and the maintenance of disinfection efficiency.

Removal of lead service lines is required if treatment is not adequate to reduce lead level.

Manganese Manganese is found in gneisses, quartzites, marbles, and other metamorphic rocks and, hence, in well waters from these formations. It is also found in many soils and sediments, such as in deep lakes and reservoirs, and in surface water. Manganese concentrations (MCL) should be not greater than 0.05 mg/1, and preferably less than 0.01, to avoid the black-brown staining of plumbing fixtures and laundry when chlorine bleach is added. The WHO guideline value for manganese is 0.1 mg/1.

Concentrations greater than 0.5 to 1.0 mg/1 may give a metallic taste to water. Concentrations above 0.05 mg/1 or less can sometimes build up coatings on sand filter media, glass parts of chlorinators, and concrete structures and in piping, which may reduce pipe capacity. When manganous manganese in solution comes in contact with air or chlorine, it is converted to the insoluble manganic state, which is very difficult to remove from materials on which it precipitates. Excess polyphosphate for sequestering manganese may prevent absorption of essential trace elements from the diet[87] it is also a source of sodium. See "Iron and Manganese Occurrence and Removal," in Chapter 2.

Mercury Episodes associated with the consumption of methylmercury-contaminated fish, bread, pork, and seed have called attention to the possible contamination of drinking water. Mercury is found in nature in the elemental and organic forms. Concentrations in unpolluted waters are normally less than 1.0 μg/1. The organic methylmercury and other alkylmercury compounds are highly toxic, affecting the central nervous system and kidneys. It is taken up by the aquatic food chain. The maximum permissible contaminant level in drinking water is 0.002 mg/1 as total mercury. The WHO guideline is 0.001 mg/1.

Methylene Blue Active Substances (MBASs) The test for MBASs also shows the presence of alkyl benzene sulfonate (ABS), linear alkylate sulfonate (LAS), and related materials that react with methylene blue. It is a measure of the apparent detergent or foaming agent and hence sewage presence. The composition of detergents varies. Household washwater in which ABS is the active agent in the detergent may contain 200 to 1,000 mg/1. Alkyl benzene sulfonate has been largely replaced by LAS, which can be degraded under aerobic conditions; if not degraded, it too will foam at greater than 1 mg/1 concentration. Both ABS and LAS detergents contain phosphates that may, if allowed to enter, fertilize plant life in lakes and streams. The decay of plants will use oxygen, leaving less for fish life and wastewater oxidation. Because of these effects, detergents containing phosphates have been banned in some areas. In any case, the presence of MBAS in well-water supply is objectionable and an indication of sewage pollution, the source of which should be identified and removed, even though it has not been found to be of health significance in the concentrations found in drinking water. The level of MBAS in a surface water is also an indicator of sewage pollution. Carbon adsorption can be used to remove MBAS from drinking water. Foaming agents should be less than 0.5 mg/1; 1.0 mg/1 is detectable by taste. Anionic (nondegradable) detergents should not exceed 0.2 mg/1.

Nitrates Nitrates represent the final product of the biochemical oxidation of ammonia. Its presence is probably due to the presence of nitrogenous organic matter of animal and, to some extent, vegetable origin, for only small quantities are naturally present in water. Septic tank systems may contribute nitrates to the groundwater if free oxygen is present. Manure and fertilizer contain large concentrations of nitrates. However, careful management practices of efficient utilization of applied manure and fertilizer by crops will reduce nitrates leaching below the root zone. Shallow (18–24-in.) septic tank absorption trenches will also permit nitrate utilization by vegetation. The existence of fertilized fields, barnyards, or cattle feedlots near supply sources must be carefully considered in appraising the significance of nitrate content. Furthermore, a cesspool may be relatively close to a well and contributing pollution without a resulting high nitrate content because the anaerobic conditions in the cesspool would prevent biochemical oxidation of ammonia to nitrites and then nitrates. In fact, nitrates may be reduced to nitrites under such conditions. In general, however, nitrates disclose the evidence of "previous" pollution of water that has been modified by self-purification processes to a final mineral form. Allowing for these important controlling factors, the following ranges in concentration may be used as a guide: low, less than 0.1 mg/1; moderate, 0.1 to 1.0 mg/1; high, greater than 1.0 mg/1. Concentrations greater than 3.0 mg/1 indicate significant manmade contribution.

The presence of more than 10 mg/1 of nitrate expressed as nitrogen, the maximum contaminant level in drinking water, appears to be the cause of methemoglobinemia, or "blue babies." The standard has also been expressed as 45 mg/1 as nitrate ion (10 mg/1 as nitrogen). Methemoglobinemia is largely a disease confined to infants less than three months old but may affect children up to age six. Boiling water containing nitrates increases the concentration of nitrates in the water. The recommended maximum for livestock is 100 mg/1.

Nitrate is corrosive to tin and should be kept at less than 2 mg/1 in water used in food canning. There is a possibility that some forms of cancer might be associated with very high nitrate levels.

Nitrates may stimulate the growth of water plants, particularly algae if other nutrients such as phosphorus and carbon are present. Nitrates seem to serve no useful purpose, other than as a fertilizer. Gould points out that

> a more objective review of literature would perhaps indicate that without any sewage additions most of our waterways would contain enough nitrogen and phosphorous (due to nonpoint pollution source) to support massive algal blooms and that the removal of these particular elements would have little effect on existing conditions.[88]

The feasible methods for the removal of nitrates are anion exchange, reverse osmosis, distillation, and electrodialysis. See "Nitrate Removal" in Chapter 2.

Nitrites Nitrites represent the first product of the oxidation of free ammonia by biochemical activity. Free oxygen must be present. Unpolluted natural waters contain practically no nitrites, so concentrations exceeding the very low value of 0.001 mg/1 are of sanitary significance, indicating water subject to pollution that is in the process of change associated with natural purification. The nitrite concentration present is due to sewage and the organic matter in the soil through which the water passes. Nitrites in concentrations greater than 1 mg/1 in drinking water are hazardous to infants and should not be used for infant feeding.

Oxidation–Reduction Potential (ORP, Also Redox) Oxidation–reduction potential is the potential required to transfer electrons from the oxidant to the reductant and is used as a qualitative measure of the state of oxidation in water treatment systems.[89] An ORP meter is used to measure in millivolts the oxidation–loss of electrons or reduction–gain of electrons.

Oxygen-Consumed Value This represents organic matter that is oxidized by potassium permanganate under the test conditions. Pollution significant from a bacteriological examination standpoint is accompanied by so little organic matter as not to significantly raise the oxygen-consumed value. For example, natural waters containing swamp drainage have much higher oxygen-consumed values than water of low original organic content that are subject to bacterial pollution. This test is of limited significance.

Para-Dichlorobenzene This chemical is a component of deodorizers, mothballs, and pesticides.[90] It generally gets into drinking water by improper waste disposal. This chemical has been shown to cause liver and kidney damage in laboratory animals such as rats and mice exposed to high levels over their lifetimes. Chemicals that cause adverse effects in laboratory animals also may cause adverse health effects in humans exposed at lower levels over long periods of time. The EPA has set the enforceable drinking water standard for *para*-dichlorobenzene at 0.075 mg/1 to reduce the risk of the adverse health effects observed in laboratory animals.

Pesticides Pesticides include insecticides, herbicides, fungicides, rodenticides, regulators of plant growth, defoliants, or desiccants. Sources of pesticides in drinking water are industrial wastes, spills and dumping of pesticides, and runoff from fields, inhabited areas, farms, or orchards treated with pesticides. Surface and groundwater may be contaminated. Conventional water treatment does not adequately remove pesticides. Powdered or granular activated carbon treatment may also be necessary. Maximum permissible contaminant levels of certain pesticides in drinking water and their uses and health effects are given in Table 1.4.

pH* The pH values of natural water range from about 5.0 to 8.5 and are acceptable except when viewed from the standpoint of corrosion. A guideline value of

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*pH is defined as the logarithm of the reciprocal of the hydrogen ion concentration. The concentration increases and the solution becomes more acidic as the pH value decreases below 7.0; the solution becomes more alkaline as the concentration decreases and the pH value increases above 7.0.

6.5 to 8.5 is suggested. The pH is a measure of acidity or alkalinity using a scale of 0.0 to 14.0, with 7.0 being the neutral point, a higher value being alkaline and lower value acidic. The bactericidal, virucidal, and cysticidal efficiency of chlorine as a disinfectant increases with a decrease in pH. The pH determination in water having an alkalinity of less than 20 mg/1 by using color indicators is inaccurate. The electrometric method is preferred in any case. The ranges of pH color indicator solutions, if used, are as follows: bromphenol blue, 3.0 to 4.6; bromcresol green, 4.0 to 5.6; methyl red, 4.4 to 6.0; bromcresol purple, 5.0 to 6.6; bromthymol blue, 6.0 to 7.6; phenol red, 6.8 to 8.4; cresol red, 7.2 to 8.8; thymol blue, 8.0 to 9.6; and phenol phthalein, 8.6 to 10.2. Waters containing more than 1.0 mg/1 chlorine in any form must be dechlorinated with one or two drops of 1/4 percent sodium thiosulfate before adding the pH indicator solution. This is necessary to prevent the indicator solution from being bleached or decolorized by the chlorine and giving an erroneous reading. The germicidal activity is greatly reduced at a pH level above 8.0. Corrosion is associated with pH levels below 6.5 to 7.0 and with carbon dioxide, alkalinity, hardness, and temperature.[91]

Phenols The WHO guideline for individual phenols, chlorophenols, and 2,4,6-trichlorophenol is not greater than 0.1 μg/1 (0.1 ppb), as the taste and odor can be detected at or above that level after chlorination. The odor of some chlorophenols is detected at 1 μg/1. In addition, 2,4,6-trichlorophenol, found in biocides and chlorinated water containing phenol, is considered a chemical carcinogen based on animal studies.[92] The guideline for pentachlorophenol in drinking water, a wood preservative, is 0.001 mg/1 based on its toxicity. It also causes objectionable taste and odor. If the water is not chlorinated, phenols up to 100 μg/1 are acceptable.[93] Phenols are a group of organic compounds that are byproducts of steel, coke distillation, petroleum refining, and chemical operations. They should be removed prior to discharge to drinking water sources. Phenols are also associated with the natural decay of wood products, biocides, and municipal wastewater discharges. The presence of phenols in process water can cause serious problems in the food and beverage industries and can taint fish. Chlorophenols can be removed by chlorine dioxide and ozone treatment and by activated carbon. The AWWA advises that phenol concentrations be less than 2.0 μg/l at the point of chlorination. Chlorine dioxide, ozone, or potassium permanganate pretreatment is preferred, where possible, to remove phenolic compounds.

Phosphorus High phosphorus concentrations, as phosphates, together with nitrates and organic carbon are often associated with heavy aquatic plant growth, although other substances in water also have an effect. Fertilizers and some detergents are major sources of phosphates. Uncontaminated waters contain 10 to 30 μg/l total phosphorus, although higher concentrations of phosphorus are also found in "clean" waters. Concentrations associated with nuisances in lakes would not normally cause problems in flowing streams. About 100 μg/l complex phosphate interferes with coagulation. Phosphorus from septic tank subsurface absorption system effluents is not readily transmitted through sandy soil and groundwater.[94] Most waterways naturally contain sufficient nitrogen and phosphorus to support massive algal blooms.

Polychlorinated Biphenyls (PCBs) Polychlorinated biphenyls give an indication of the presence of industrial wastes containing mixtures of chlorinated byphenyl compounds having various percentages of chlorine. Organochlorine pesticides have a similar chemical structure. The PCBs cause skin disorders in humans and cancer in rats. They are stable and fire resistant and have good electrical insulation capabilities. They have been used in transformers, capacitors, brake linings, plasticizers, pumps, hydraulic fluids, inks, heat exchange fluids, canvas waterproofing, ceiling tiles, fluorescent light ballasts, and other products. They are not soluble in water but are soluble in fat. They cumulate in bottom sediment and in fish, birds, ducks, and other animals on a steady diet of food contaminated with the chemical. Concentrations up to several hundred and several thousand milligrams per liter have been found in fish, snapping turtles, and other aquatic life. Polybrominated biphenyl, a derivative of PCB, is more toxic than PCB. Aroclor is the trade name for a PCB mixture used in a pesticide. The manufacture of PCBs was prohibited in the United States in 1979 under the Toxic Substances Control Act of 1976. The use in transformers and electromagnets was banned after October 1985 if they pose an exposure risk to food or animal feed. Continued surveillance of existing equipment and its disposal is necessary for the life of the equipment. The toxicity of PCB and its derivatives appears to be due to its contamination with dioxins. The Food and Drug Administration (FDA) action levels are 1.5 mg/l in fat of milk and dairy products; 3 mg/l in poultry and 0.3 mg/l in eggs; and 2 mg/l in fish and shellfish. The MCL for drinking water is 0.0005 mg/l with zero as the EPA MCLG. The OSHA permissible 8-hour time-weighted average (TWA) airborne exposure limit is 0.5 mg/m^3 for PCBs containing 42 percent chlorine.[95] The National Institute of Occupational Safety and Health (NIOSH) recommended that the 8-hour TWA exposure by inhalation be limited to 1.0 μg/m^3 or less.[96] A level not exceeding 0.002 μg/l is suggested to protect aquatic life.[97] The PCBs are destroyed at 2000°F (1093°C) and 3 percent excess oxygen for 2 seconds contact time. They are vaporized at 1584°F (862°C). The PCB contamination of well water has been associated with leakage from old submersible well pumps containing PCB in capacitors. These pumps were manufactured between 1960 and 1978, are oil cooled rather than water cooled, and have a two-wire lead rather than three-wire. Pumps using 220-volt service would not be involved.[98] Activated carbon adsorption and ozonation plus UV are possible water treatments to remove PCBs.

Polynuclear Aromatic Hydrocarbons Polynuclear aromatic hydrocarbons such as fluoranthene, 3,4-benzfluoranthene, 11,12-benzfluoranthene, 3,4-benzpyrene, 1,12-benzperyline, and indeno [1,2,3-*cd*] pyrene are known carcinogens and are potentially hazardous to humans. The WHO set a limit of 0.2 μg/l for the sum of these chemicals in drinking water, comparable in quality with unpolluted groundwater. Because of its carcinogenicity, a guideline value of 0.01 μg/l is proposed for benzo[*a*]pyrene in drinking water. It is also recommended that the use of cool-tar-based pipe linings be discontinued. [99]

Polysaccharides In soft drink manufacturing, polysaccharides* in surface waters may be found in the water used. In waters of low pH, the polysaccharides come out of solution to form a white precipitate. The CO_2 in carbonated water is also sufficient to cause this. Coagulation and sedimentation or reverse osmosis treatment can remove polysaccharides.

Brewing water should ideally be low in alkalinity and soft but high in sulfates.[100]

Radioactivity The maximum contaminant levels for radioactivity in drinking water are given in Table 1.4. The exposure to radioactivity from drinking water is not likely to result in a total intake greater than recommended by the Federal Radiation Council. Naturally occurring radionuclides include Th-232, U-235, and U-238 and their decay series, including radon and radium 226 and 228. They may be found in well waters, especially those near uranium deposits. (Radium is sometimes found in certain spring and well supplies.) Since these radionuclides emit alpha and beta radiation (as well as gamma), their ingestion or inhalation may introduce a serious health hazard, if found in well-water supplies.[101]Possible manmade sources of radionuclides in surface waters include fallout (in soluble form and with particulate matter) from nuclear explosions in precipitation and runoff, releases from nuclear reactors and waste facilities, and manufacturers. Radon is the major natural source of radionuclides.

Radon Radon is a natural decay product of uranium and is a byproduct of uranium used in industry and the manufacture of luminescent faces of clocks and instruments. It is also found in soil, rock, and well water and is readily released when water is agitated such as in a washing machine (clothes and dish), when water flows out of a faucet, and when water is sprayed from a shower head. Radon is particularly dangerous when released and inhaled in an enclosed space such as indoors. Radon-222 is emitted from tailings at uranium mill sites.

The EPA estimates that 10,000 pCi/l in water will result in a radon air concentration of about 1 pCi/l. The EPA has proposed a maximum contaminant level of 300 pCi/l for drinking water supplies.

Radon can be removed from water by aeration—packed tower or diffused air, filtration through granular activated carbon, ion exchange, and reverse osmosis. The concentration of radon in removal raises a disposal problem.

Selenium Selenium is associated with industrial pollution (copper smelting) and vegetation grown in soil containing selenium. It is found in meat and other foods. Selenium causes cancers and sarcomas in rats fed heavy doses. Chronic exposure to excess selenium results in gastroenteritis, dermatitis, and central

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*One of a group of carbohydrates.

nervous system disturbance.[102] Selenium is considered an essential nutrient and may provide protection against certain types of cancer. Selenium in drinking water should not exceed the MCL of 0.05 mg/l. An intake of 25 or 50 μg/day is not considered harmful.

Silver The secondary MCL for silver in drinking water is 0.10 mg/l. Silver is sometimes used to disinfect small quantities of water and in home faucet purifiers. Colloidal silver may cause permanent discoloration of the skin, eyes, and mucous membranes. A continuous daily dose of 400 μg of silver may produce the discoloration (argyria). Only about 10 percent of the ingested silver is absorbed.[103]

Sodium Persons on a low-sodium diet because of heart, kidney, or circulatory (hypertension) disease or pregnancy should use distilled water if the water supply contains more than 20 mg/l of sodium and be guided by a physician's advice. The consumption of 2.0 liters of water per day is assumed. Water containing more than 200 mg/l sodium should not be used for drinking by those on a moderately restricted sodium diet. It can be tasted at this concentration when combined with other anions. Many groundwater supplies and most home-softened (using ion exchange) well waters contain too much sodium for persons on sodium-restricted diets. If the well water is low in sodium (less than 20 mg/l) but the water is softened by the ion exchange process because of excessive hardness, the cold-water system can be supplied by a line from the well that bypasses the softener and low-sodium water can be made available at cold-water taps. A home water softener adds 0.46 times the hardness removed as $CaCO_3$. Sodium can be removed by reverse osmosis, distillation, and cation exchange, but it is costly. A laboratory analysis is necessary to determine the exact amount of sodium in water. The WHO guideline for sodium in drinking water is 200 mg/l. Common sources of sodium, in addition to food, are certain well waters, ion exchange water-softening units, water treatment chemicals (sodium aluminate, lime-soda ash in softening, sodium hydroxide, sodium bisulfite, and sodium hypochlorite), road salt, and possibly industrial wastes. Sodium added in fluoridation and corrosion control is not significant.

Specific Electrical Conductance Specific electrical conductance is a measure of the ability of a water to conduct an electrical current and is expressed in micromhos per cubic centimeters of water at 77°F (25°C). Because the specific conductance is related to the number and specific chemical types of ions in solution, it can be used for approximating the dissolved-solids content in the water, particularly the mineral salts in solution if present. The higher the conductance, the more mineralized the water and its corrosivity. Different minerals in solutions give different specific conductance. Commonly, the amount of dissolved solids (in milligrams per liter) is about 65 percent of the specific conductance. This relationship is not constant from stream to stream from well to well, and it may even vary in the same source with changes in the composition of the water.

Specific conductance is used for the classification of irrigation waters. In general, waters of less than 200 μmho/cm^3 are considered acceptable, and conductance in excess of 300 μmho/cm^3 unsuitable. Good fresh waters for fish in the United States are reportedly under 1100 μmho/cm^3.[104] Wastewater with a conductivity up to 1,200 to 4,000 μmho/cm^3 may be acceptable for desert reclamation. Electrical conductivity measurements give a rapid approximation of the concentration of dissolved solids in milligrams per liter.

Sulfates The sulfate content should not exceed the secondary MCL of 250 mg/l. The WHO guideline is 400 mg/l.[105] With zeolite softening, calcium sulfate or gypsum is replaced by an equal concentration of sodium sulfate. Sodium sulfate (or Glauber salts) in excess of 200 mg/l, magnesium sulfate (or Epsom salts) in excess of 390 to 1,000 mg/l, and calcium sulfate in excess of 600 to 800 mg/l are laxative to those not accustomed to the water. Magnesium sulfate causes hardness; sodium sulfate causes foaming in steam boilers. Sulfate is increased when aluminum sulfate is used in coagulation. High sulfates also contribute to the formation of scale in boilers and heat exchangers. Concentrations of 300 to 400 mg/l cause a taste. Sulfates can be removed by ion exchange, distillation, reverse osmosis, or electrodialysis. Sulfates are found in surface waters receiving industrial wastes such as those from sulfate pulp mills, tanneries, and textile plants. Sulfates also occur in many waters as a result of leaching from gypsum-bearing rock.

Total Dissolved Solids (TDS) The total solid content should be less than 500 mg/l; however, this is based on the industrial uses of public water supplies and not on public health factors. Higher concentrations cause physiological effects and make drinking water less palatable. Dissolved solids, such as calcium, bicarbonates, magnesium, sodium, sulfates, and chlorides, cause scaling in plumbing above 200 mg/l. The TDS can be reduced by distillation, reverse osmosis, electrodialysis, evaporation, ion exchange, and, in some cases, chemical precipitation. Water with more than 1000 mg/l of dissolved solids is classified as *saline*, irrespective of the nature of the minerals present.[106] The USGS classifies water with less than 1000 mg/l as fresh, 1,000 to 3,000 as slightly saline, 3,000 to 10,000 as moderately saline, 10,000 to 35,000 as very saline, and more than 35,000 as briny.

1,1,1-Trichloroethane This chemical is used as a cleaner and degreaser of metals.[107] It generally gets into drinking water by improper waste disposal. This chemical has been shown to damage the liver, nervous system, and circulatory system of laboratory animals such as rats and mice exposed at high levels over their lifetimes. Some industrial workers who were exposed to relatively large amounts of this chemical during their working careers also suffered damage to the liver, nervous system, and circulatory system. Chemicals that cause adverse effects among exposed industrial workers and in laboratory animals may also cause adverse health effects in humans exposed at lower levels over long periods of time. The EPA has set the enforceable drinking water standard for 1,1,1-trichloroethane at 0.2 mg/l to protect against the risk of adverse health effects observed in humans and laboratory animals.

Trichloroethylene This chemical is a common metal-cleaning and dry-cleaning fluid.[108] It generally gets into drinking water by improper waste disposal. This chemical has been shown to cause cancer in laboratory animals such as rats and mice when exposed at high levels over their lifetimes. Chemicals that cause cancer in laboratory animals may also increase the risk of cancer in humans exposed at lower levels over long periods of time. The EPA has set forth the enforceable drinking water standard for trichloroethylene at 0.005 mg/l to reduce the risk of cancer or other adverse health effects observed in laboratory animals.

Trihalomethanes Trihalomethanes (THMs) and other nonvolatile, higher molecular weight compounds are formed by the interaction of free chlorine with humic and fulvic substances and other organic precursors produced either by normal organic decomposition or by metabolism of aquatic biota. The precursor level is determined through testing by prechlorination of a sample and then analyzing the sample after seven days storage under controlled temperature and pH. A rapid surrogate THM measurement can be made using UV absorbent measurement. Two gas chromatographic analytic techniques are acceptable by the EPA for THM analysis. The THMs include chloroform (trichloromethane), bromoform (tribromomethane), dibromochloromethane, bromodichloromethane, and iodoform (dichloroiodomethane). Toxicity, mutagenicity, and carcinogenicity have been suspected as being associated with the ingestion of trihalomethanes. The EPA has stated that:

> epidemiological evidence relating THM concentrations or other drinking water quality factors and cancer morbidity-mortality is not conclusive but suggestive. Positive statistical correlations have been found in several studies,* but causal relationships cannot be established on the basis of epidemiological studies. The correlation is stronger between cancer and the brominated THMs than for chloroform.[109]

Chloroform is reported to be carcinogenic to rats and mice in high doses and hence is a suspected human carcinogen. The Epidemiology Subcommittee of the National Research Council (NRC) says that cancer and THM should not be linked.[110] The Report on Drinking Water and Health, NRC Safe Drinking Water and Health, states: “A review of 12 epidemiological studies failed either to support or refute the results of positive animal bioassays suggesting that certain trihalomethanes, chloroform for example, may cause cancer in humans.”[111] However, the National Drinking Water Advisory Council, based on studies in the review and evaluation by the National Academy of Sciences, the work done by

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*The reliability and accuracy of studies such as these are often subject to question.

the National Cancer Institute, and other research institutions within the EPA, has accepted the regulation of trihalomethanes on "the belief that chloroform in water does impose a health threat to the consumer."[112] The EPA has established a standard of 80 μg/l for total THMs for public water supplies. The WHO guideline for chloroform is 30 μg/l[113] and 35 μg/l for THM in Canada.

Uranyl Ion This ion may cause damage to the kidneys. Objectionable taste and color occur at about 10 mg/l. It does not occur naturally in most waters above a few micrograms per liter. The taste, color, and gross alpha MCL will restrict uranium concentrations to below toxic levels; hence, no specific limit is proposed.[114]

Vinyl Chloride This chemical is used in industry and is found in drinking water as a result of the breakdown of related solvents.[115] The solvents are used as cleaners and degreasers of metals and generally get into drinking water by improper waste disposal. This chemical has been associated with significantly increased risks of cancer among certain industrial workers who were exposed to relatively large amounts of this chemical during their working careers. This chemical has also been shown to cause cancer in laboratory animals when exposed at high levels over their lifetimes. Chemicals that cause increased risk of cancer among exposed industrial workers and in laboratory animals also may increase the risk of cancer in humans exposed at lower levels over long periods of time. The EPA has set the enforceable drinking water standard for vinyl chloride at 0.002 mg/l to reduce the risk of cancer or other adverse health effects observed in humans and laboratory animals. Packed-tower aeration removes vinyl chloride.

Zinc The concentration of zinc in drinking water (goal) should be less than 1.0 mg/l. The MCL and the WHO guideline is 5.0 mg/l.[116]Zinc is dissolved by surface water. A greasy film forms in surface water containing 5 mg/l or more zinc upon boiling. More than 5.0 mg/l causes a bitter metallic taste and 25 to 40 mg/l may cause nausea and vomiting. At high concentrations, zinc salts impart a milky appearance to water. Zinc may contribute to the corrosiveness of water. Common sources of zinc in drinking water are brass and galvanized pipe and natural waters where zinc has been mined. Zinc from zinc oxide in automobile tires is a significant pollutant in urban runoff.[117] The ratio of zinc to cadmium may also be of public health importance. Zinc deficiency is associated with dwarfism and hypogonadism.[118] Zinc is an essential nutrient. It can be reduced by ion exchange, softening, reverse osmosis, and electrodialysis.

Drinking Water Additives

Potentially hazardous chemicals or contaminants may inadvertently be added directly or indirectly to drinking water in treatment, well drilling, and distribution. Other contaminants potentially may leach from paints, coatings, pumps, storage tanks, distribution system pipe and plumbing systems, valves, pipe fittings, and other equipment and products.

Chemicals (direct additives) used in water treatment for coagulation, corrosion control, and other purposes may contain contaminants such as heavy metals or organic substances that may pose a health hazard. In addition, significant concentrations of organic and inorganic contaminants (indirect additives) may leach or be extracted from various drinking water system components.

Since its inception, the EPA has maintained an advisory list of acceptable products for drinking water contact, but this function was transferred to the private sector on April 7, 1990. In 1985, the EPA provided seed funding for a consortium to establish a program for setting standards and for the testing, evaluation, inspection, and certification to control potentially hazardous additives. The consortium included the AWWA, the American Water Works Association Research Foundation (AWWARF), the Association of State Drinking Water Administrators (ASDWA), and the National Sanitation Foundation (NSF).

In 1988, the NSF published American National Standards Institute (ANSI)/NSF Standard 60, Drinking Water Treatment Chemicals—Health Effects, and ANSI/NSF Standard 61, Drinking Water System Components—Health Effects.[119]The ANSI approved NSF Standards 60 and 61 in May of 1989.

Third-party certification organizations, like the NSF, Underwriters Laboratories (UL), and the Safe Water Additives Institute,[120]* can certify products for compliance with the ANSI/NSF standards. In addition to the NSF listing of certified products, the AWWA plans to maintain and make available a directory of all products certified as meeting the ANSI/NSF standards.

In mid-1990, the ANSI announced a program to "certify the certifiers." Because each state regulates drinking water additives products, the ANSI program is expected to provide the basis for state acceptance of independent certification organizations to test and evaluate equipment and products for compliance with the standards. The ANSI program includes minimum requirements for certification agencies that address chemical and microbiological testing, toxicology review and evaluation, factory audits, follow-up evaluations, marking, contracts and policies, and quality assurance. Many state drinking water regulations and rules require independent third-party certification of additives products.

Water Quantity

The quantity of water used for domestic purposes will generally vary directly with the availability of the water, habits of the people, cost of water, number and type of plumbing fixtures provided, water pressure, air temperature, newness of a community, type of establishment, metering, and other factors. Wherever possible, the actual water consumption under existing or similar circumstances and the number of persons served should be the basis for the design of a water and sewage system. Special adjustment must be made for unaccounted-for water

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*The NSF is accredited by the ANSI, UL has applied for accrediation, and the Safe Water Additives Institute is developing a program for ANSI review (*AWWA MainStream*, May 1991).

and for public, industrial, and commercial uses. The average per-capita municipal water use has increased from 150 gpd in 1960 to 168 gpd in 1975 to 183 gpd in 1980 and remained relatively steady at 179 gpd in 1995. Approximately 70 gal is residential use, 50 gal industrial, 35 gal commercial, and 10 gal public and 14 gal is lost.[121] Included is water lost in the distribution system and water supplied for firefighting, street washing, municipal parks, and swimming pools. USGS estimated rural water use at 68 gpd in 1975 and 79 gpd in 1980.[122]

Table 1.14 gives estimates of water consumption at different types of places and in developing areas of the world. Additions should be made for car washing, lawn sprinkling, and miscellaneous uses. If provision is made for firefighting requirements, then the quantity of water provided for this purpose to meet fire underwriters' standards will be in addition to that required for normal domestic needs in small communities.

Developing Areas of the World Piped water delivery to individual homes and waterborne sewage disposal are not affordable in many developing countries. This calls for sequential or incremental improvements from centrally located hand pumps to water distribution systems. Social, cultural, and economic conditions, hygiene education, and community participation must be taken into account in project selection and design.[123] Community perception of needs, provision of local financial management, operation, and maintenance must be taken into consideration and assured before a project is started. The annual cost of water purchased from a water vendor may equal or exceed the cost of piped metered water. In addition, much time is saved where water must be hauled from a stream. Hand pumps, where used, should be reliable, made of corrosion-resistant materials, with moving parts resistant to abrasion, including sand, and readily maintained at the local level. A detailed analysis of hand pump tests and ratings has been made by Arlosoroff et al.[124] It is important to keep mechanical equipment to a minimum and to train local technicians. Preference should be given to drilled wells where possible. For surface-water supplies, slow sand filters are generally preferred over the more complex rapid sand filters.

Water Conservation

Water conservation can effect considerable saving of water with resultant reduction in water treatment and pumping costs and wastewater treatment. With water conservation, development of new sources of water and treatment facilities and their costs can be postponed or perhaps made unnecessary, and low-distribution system water pressure situations are less likely. However, the unit cost of water to the consumer may not be reduced; it may actually increase because the fixed cost will remain substantially the same. The revenue must still be adjusted to meet the cost of water production and distribution.

Water conservation can be accomplished, where needed, by a continuing program of leak detection and repair in the community distribution system and in buildings; use of low water-use valves and plumbing fixtures; water pressure and flow control in the distribution system and in building services (orifices);

TABLE 1.14 Guides for Water Use in Design

Type of Establishment	gpd[a]
Residential	
Dwellings and apartments (per bedroom)	150
Rural	60
Suburban	75
Urban	180
Temporary Quarters	
Boarding houses	65
Additional (or nonresident boarders)	10
Campsites (per site), recreation vehicle with individual connection	100
Campsites, recreational vehicle, with comfort station	40–50
Camps without toilets, baths, or showers	5
Camps with toilets, without baths or showers	25
Camps with toilets and bathhouses	35–50
Cottages, seasonal with private bath	50
Day camps	15–20
Hotels	65–75
Mobile home parks (per unit)	125–150
Motels	50–75
Public Establishments	
Restaurants (toilets and kitchens)	7–10
Without public toilet facilities	$2\frac{1}{2}$–3
With bar or cocktail lounge, additional	2
Schools, boarding	75–100
Day with cafeteria, gymnasium, and showers	25
Day with cafeteria, without gymnasium and shower	15
Hospitals (per bed)	175–400
Institutions other than hospitals (per bed)	75–125
Places of public assembly	3–10
Turnpike rest areas	5
Turnpike service areas (per 10% of cars passing)	15–20
Prisons	120
Amusement and Commercial	
Airports (per passenger), add for employees and special uses	3–5
Car wash (per vehicle)	40
Country clubs, excluding residents	25
Day workers (per shift)	15–35
Drive-in theaters (per car space)	5
Gas station (per vehicle serviced)	10
Milk plant, pasteurization (per 100 lb of milk)	11–25
Movie theaters (per seat)	3
Picnic parks with flush toilets	5–10
Picnic parks with bathhouse, showers, bathrooms	20
Self-service laundries (per machine) (or 50 gal per customer)	400–500

(*continues*)

TABLE 1.14 (*continued*)

Type of Establishment	gpd[a]
Shopping center (per 1,000 ft^2 floor area), add for employees, restaurants, etc.	250
Stores (per toilet room)	400
Swimming pools and beaches with bathhouses	10
Fairgrounds (based on daily attendance), also sports arenas	5
Farming (per Animal)	
Cattle or steer	12
Milking cow, including servicing	35
Goat or sheep	2
Hog	4
Horse or mule	12
Cleaning milk bulk tank, per wash	30–60
Milking parlor, per station	20–30
Liquid manure handling, cow	1–3
Poultry (per 100)	
Chickens	5–10
Turkeys	10–18
Cleaning and sanitizing equipment	4

Miscellaneous Home Water Use	Estimated (gal)
Toilet, tank, per use[b]	1.6–3.5
Toilet, flush valve 25 psi (pounds per square inch), per use[b]	1.6–3.5
Washbasin, gpm[b]	2–3
Bathtub	30/use
Shower, gpm[b]	2.5–3
Dishwashing machine, domestic, 15.5/load	9.5–
Garbage grinder, 2/day	1–
Automatic laundry machine, domestic	
34–57/load, top load	
22–33/load, front load	
Garden hose	
$\frac{5}{8}$ in., 25-ft head	200/hr
$\frac{3}{4}$ in., $\frac{1}{4}$ in. nozzle, 25-ft head	300/hr
Lawn sprinkler, 3,000-ft^2 lawn, 1 in. per week	120/hr
Air conditioner, water-cooled, 3-ton, 8 hr per day	1,850/week 2,880/day

Household Water Use	Percent	Municipal Water Use	Percent
Toilet flushing	36	Residential	38
Bathing	26	Industrial: factories	27
Drinking and cooking	5	Commercial: hospitals, restaurants	19
Dishwashing	6	Public: fires, parks	6
Clothes washing	15	Waste: leaks	10
Cleaning and miscellaneous	12		

TABLE 1.14 (*continued*)

Water Demand per Dwelling Unit: Surburban, Three-Bedrooms (BR)	Water Use (gpd)
Average day	300
Maximum day	600
Maximum hourly rate	1500
Maximum hourly rate with appreciable lawn watering	1800

Home Water System (Minimums)	2 BR	3 BR	4 BR	5 BR
Pump capacity, gal/hr	250	300	360	450
Pressure tank, gal minimum	42	82	82	120
Service line from pump, diameter (in.)[c]	$\frac{3}{4}$	$\frac{3}{4}$	1	$1\frac{1}{4}$

Other Water Use	Gallons
Fire hose, $1\frac{1}{2}$ in., $\frac{1}{2}$ in. nozzle, 70-ft head	2400/hr
Drinking fountain, continuous flowing	75/hr
Dishwashing machine, commercial	
Stationary rack type, 15 psi	6–9/min
Conveyor type, 15 psi	4–6/min
Fire hose, home, 10 gpm at 60 psi for 2 hr, $\frac{3}{4}$ in.	600/hr
Restaurant, average	35/seat
Restaurant, 24-hr	50/seat
Restaurant, tavern	20/seat
Gas station	500/set of pumps
Developing Areas of the World	
One well or tap/200 persons; controlled tap or hydrant:	
Fordilla or Robovalve type	
Average consumption, 5 gal/capita/day at well or tap, water carried	
Water system design, 30 gal/capita/day (10 gal/capita is common)	
(50 gal is recommended)	
Pipe size, 2 in. and preferably larger (1 and $1\frac{1}{2}$ in. common)	
Drilled well, cased, 6–8 in. diameter	
Water system pressure, 20 lb/in.^{2}	
(Keep mechanical equipment to a minimum.)	

Developing Country[d]	Liters	Gallons
China	80	21
Africa	15–35	4–9
Southeast Asia	30–70	8–19
Western Pacific	30–90	8–24
Eastern Mediterranean	40–85	11–23
Europe (Algeria, Morocco, Turkey)	20–65	5–17
Latin America and Caribbean	70–190	19–51
World average	35–90	9–24

[a] Per person unless otherwise stated.

[b] Water conservation fixtures. See text.

[c] Service lines less than 50 ft long, brass or copper. Use next larger size if iron pipe is used. Use minimum $\frac{1}{3}$-in. service with flush valves. Minimum well yield, 5 gal/min.

[d] Assumes hydrant or hand pump available within 200 m; 70 liters per capita per day (Lpcd) or more could mean house or central courtyard outlet.) Mechanical equipment kept at a minimum.

universal metering and price adjustment; conservation practices by the consumer; and a rate structure that encourages conservation.

Leak detection activities would include metering water use and water production balance studies; routine leak detection surveys of the distribution system; investigation of water ponding or seepage reports and complaints; and reporting and prompt follow-up on leaking faucets, running flushometer valves and water closet ball floats, and other valves. Universal metering will make possible water balance studies to help detect lost water and provide a basis for charging for water use. Meters must be periodically tested for accuracy and read. However, centralized remote meter reading can simplify this task. Reduction in water use, perhaps 20 percent, may be temporary in some instances; many users may not economize.

Low water-use plumbing fixtures and accessories would include the low-flush water closets; water-saving shower-head flow controls, spray taps, and faucet aerators; and water-saving clothes washers and dishwashers. In a dormitory study at a state university, the use of flow control devices (pressure level) on shower heads effected a 40 to 60 percent reduction in water use as a result of reducing the shower-head flow rates from 5.5 gpm to 2.0 to 2.5 gpm.[125] Plumbing codes should require water-saving fixtures and pressure control in new structures and rehabilitation projects. For example, only water-efficient plumbing fixtures meeting the following standards are permitted to be sold or installed in New York State*:

Sink 3 gpm, lavatory faucet not greater than 2 gpm;
Shower heads not greater than 3 gpm;
Urinals and associated flush valve, if any, not greater than 1 gal of water per flush;
Toilets and associated flush valve, if any, not greater than 1.6 gal of water per flush
Drinking fountains, sinks, and lavatories in public restrooms with self-closing faucets[126]

Special fixtures such as safety showers and aspirator faucets are exempt, and the commissioner may permit use of fixtures not meeting standards if necessary for proper operation of the existing plumbing or sewer system.

On March 1, 1989, Massachusetts became the first state to require ultra-low-flow toilets using 1.6 gal per flush. The federal government adopted (effective January 1991) the following standards[127]:

Toilets 1.6 gal per flush
Urinals 1.0 gal per flush

*The Washington Suburban Sanitary District plumbing code has similar requirements. (R. S. McGarry and J. M. Brusnighan, "Increasing Water and Sewer Rate Schedules: A Tool for Conservation," *J. Am. Water Works Assoc*. (September 1979): 474–479.) The National Small Flows Clearinghouse, West Virginia University, reported in *Small Flows*, July 1991, that 12 states have adopted low-flow plumbing fixture regulations.

Showerheads 2.5 gpm
Lavatory faucets 2.0 gpm
Kitchen faucets 2.5 gpm

An ultra-low-flush toilet using 0.8 gal per flush was found to perform equal to or better than the conventional toilet.[128] One might also add to the list of water conservation possibilities, where appropriate, use of the compost toilet, recirculating toilet, chemical toilet, incinerator toilet, and various privies. Air-assisted half-gallon flush toilets are also available.[129]

Pressure-reducing valves in the distribution system (pressure zones) to maintain a water pressure of 20 to 40 psi at fixtures will also reduce water use. A water saving of 6 percent can be expected at new single-family homes where water pressure in the distribution system is reduced from 80 to 30 to 40 psi based on HUD studies.[130] The potential water saving through pressure control is apparent from the basic hydraulic formulas:

$$Q = VA \quad Q = (2gpw)^{1/2} \times AQ = (2gh)^{1/2} \times A$$

where

$Q =$ cfs
$V =$ fps
$A =$ ft^2
$g =$ 32.2 ft/sec/sec
$p =$ lb/ft^2
$w =$ lb/ft^3 (62.4)
$h =$ ft of water

which show that the quantity of water flowing through a pipe varies with the velocity or the square root of the pressure head. For example, a pressure reduction from 80 to 40 psi will result in a flow reduction of 29 percent, but the actual water savings would probably be 6 percent, as previously noted.

The success of water-use conservation also depends largely on the extent to which consumers are motivated. They can be encouraged to repair leaking faucets and running toilets immediately; to not waste water; to understand that a leak causing a 1/8-inch-diameter stream adds up to 400 gal in 24 hours, which is about the amount of water used by a family of five or six in one day; to purchase a water-saving clothes washer and dishwasher; to add 1-liter bottles or a “dam” to the flush tank to see if the closet still flushes properly; to install water-saving shower heads and not use the tub; to install mixing faucets with single-lever control; and to install aerators on faucets. Consumer education and motivation must be a continuing activity. In some instances, reuse of shower, sink, and laundry wastewater for gardens is feasible.[131]

Water Reuse

An additional way of conserving drinking water and avoiding or minimizing large capital expenditures is to reduce or eliminate its use for nonpotable purposes by substituting treated municipal wastewater. This could increase the available supply for potable purposes at least cost and reduce the wastewater disposal problem. However, a distinctly separate nonpotable water system and monitoring protocol would be required.

Discussion of wastewater reuse should clearly distinguish between direct reuse and indirect reuse. In *direct reuse*, the additional wastewater treatment (such as storage, coagulation, flocculation, sedimentation, sand or anthracite filtration or granular activated-carbon filtration, and disinfection) is usually determined by the specific reuse. The wastewater is reclaimed for *nonpotable* purposes such as industrial process or cooling water, agricultural irrigation, groundwater recharge, desert reclamation, and fish farming; lawn, road median, tree farm, and park irrigation; landscape and golf-course watering; and toilet flushing. The treated wastewater must *not* be used for drinking, culinary, bathing, or laundry purposes. The long-term health effects of using treated wastewater for potable purposes are not fully understood at this time, and fail-safe, cost-effective treatment technology for the removal of all possible contaminants is not currently available.[132] In *indirect reuse*, wastewater receiving various degrees of treatment is discharged to a surface water or a groundwater aquifer, where it is diluted and after varying detention periods and treatment may become a source of water for potable purposes. *Recycling* is the reuse of wastewater, usually by the original user.

Direct municipal wastewater reuse, where permitted, would require a clearly marked dual water system, one carrying potable water and the other reclaimed wastewater. It has been estimated that the average person uses only about 25 to 55 gal of water per day for potable purposes.[133] The reclaimed water is usually bacteriologically safe but questionable insofar as other biological or organic and inorganic chemical content is concerned. A dye added to the reclaimed water would help avoid its inadvertent use for potable purposes. Okun emphasizes that the reclaimed or nonpotable water should.

> equal the quality of the potable systems that many communities now provide—the health hazard that results from the continuous ingestion of low levels of toxic substances over a period of years would not be present.[134]

Advanced wastewater treatment, monitoring, and surveillance cannot yet in practice guarantee removal of all harmful substances (microcontaminants) from wastewater at all times. However, numerous projects are now investigating reuse of water for potable purposes.[135]* More knowledge is needed concerning acute and long-term effects on human health of wastewater reuse.[136] In Windhoek, Namibia, Southwest Africa, reclaimed sewage, which is reported to contain no industrial wastes, blended with water from conventional sources has occasionally been used for drinking for many years without any apparent problems. The sewage is given very elaborate treatment involving some 18 unit processes.[137]

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*The July 1985 issue of the *Journal of the American Water Works Association* is devoted to wastewater reuse.

Monitoring is done for *Salmonella, Shigella*, enteropathogenic *E. coli, Vibrio*, enterovirus, *Schistosoma*, viral hepatitis, meningitis, and nonbacterial gastroenteritis, in addition to turbidity and organic and inorganic chemicals. None of the pathogens was associated with the reclaimed wastewater.

More emphasis is needed on the removal of hazardous substances at the source and on adequate wastewater treatment prior to its discharge to surface and underground water supply sources. This will at least reduce the concentrations of contaminants discharged from urban and industrial areas and, it is hoped, the associated risks.

In any case, it is axiomatic that, in general, the cleanest surface and underground water source available should be used as a source of drinking water, and water conservation practiced, before a polluted raw water source is even considered, with cost being secondary.

SOURCE AND PROTECTION OF WATER SUPPLY

General

The sources of water supply are divided into two major classifications: groundwater and surface water. To these should be added rainwater and demineralized water. The groundwater supplies include dug, bored, driven and drilled wells, rock and sand or earth springs, and infiltration galleries. The surface-water supplies include lake, reservoir, stream, pond, river, and creek supplies.

The location of groundwater supplies should take into consideration the recharge tributary wellhead area,[138] the probable sources and travel of pollution through the ground, the well construction practices and standards actually followed, depth of well casing and grouting, and the type of sanitary seal provided at the point where the pump line(s) pass out of the casing.

Wellhead area has been defined under the 1986 Amendments to the Safe Drinking Water Act as "the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield." The time of travel of a potential contaminant, distance, drawdown, flow boundaries, and assimilative capacity are critical factors in determining the wellhead protection area.[139] Some of the other hydrogeological considerations, in addition to well drawdown, radius of influence,* withdrawal rate, recharge area, and aquifer formation, are the hydraulic gradient, natural dilution, filtration, attenuation, and degradation of the contaminant in its movement through the zone of aeration (unsaturated zone) to the saturated zone and into the water table of the wellhead drainage area. These factors must be evaluated in the light of available topographic, geologic, and engineering information and the practicality of land-use controls, conservation easements, and dedication of land to parks to

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*Circular only with flat water table, when drawdown cone of depression is 99 percent stabilized.

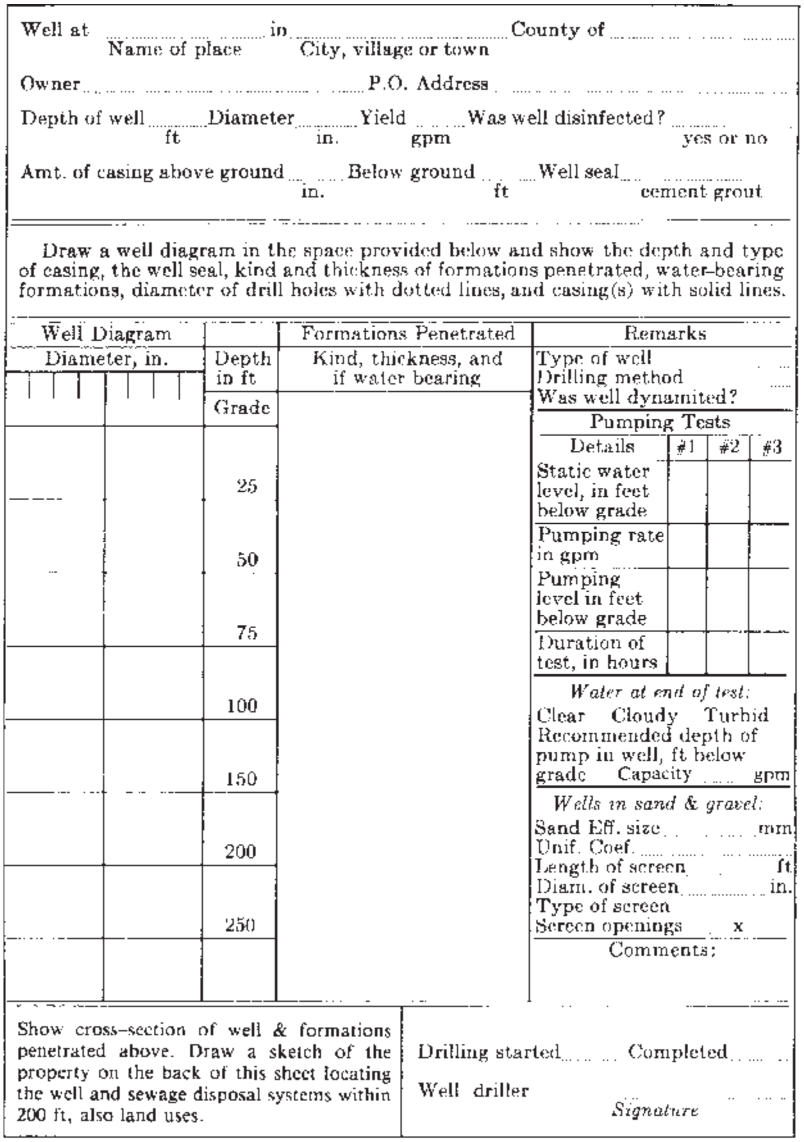
effectively prevent or adequately minimize the potential effects of contaminants on the recharge area. See earlier discussion under "Sanitary Survey and Water Sampling."

The chemical quality of shallow groundwater (8–20 ft) and its quantity can be expected to vary substantially throughout the year and after heavy rains, depending on the soil depth and characteristics in the unsaturated zone above the water table.

It is sometimes suggested that the top of a well casing should terminate below the ground level or in a pit. This is not considered good practice except when the pit can be drained above flood level to the surface by gravity or to a drained basement. Frost-proof sanitary seals with pump lines passing out horizontally from the well casing are generally available. Some are illustrated later in Figures 1.7 through 1.10.

In order that the basic data on a new well may be recorded, a form such as the well driller's log and report shown in Figure 1.4 should be completed by the well driller and kept on file by the owner for future reference. A well for a private home should preferably have a capacity (well yield) of at least 500 gal/hr, but 300 gal/hr is usually specified as a minimum for domestic water use in serving a three-bedroom home. The long-term yield of a well is dependent on the seasonal static water level, other withdrawals from the aquifer, the recharge area and storage in the aquifer, and the hydraulic characteristics of the aquifer. Because of this and the uncertainty of when stabilized drawdown is reached, the determined well yield should be reduced to compensate for long-term use and possible decline of aquifer yield. Pumping tests should therefore ensure that the water level in the well returns to the original static level. See Tables 1.14 and 1.15.

Surface-water supplies are all subject to continuous or intermittent pollution and must be treated to make them safe to drink. One never knows when the organisms causing typhoid fever, gastroenteritis, giardiasis, infectious hepatitis A, or dysentery, in addition to organic and inorganic pollutants, may be discharged or washed into the water source. The extent of the treatment required will depend on the results of a sanitary survey made by an experienced professional, including physical, chemical, and microbiological analyses. The minimum required treatments are coagulation, flocculation, sedimentation, filtration, and chlorination, unless a conditional waiver is obtained from the regulatory agency. If more elaborate treatment is needed, it would be best to abandon the idea of using a surface-water supply and resort to a protected groundwater supply if possible and practical. Where a surface supply must be used, a reservoir or a lake that provides at least 30 days *actual* detention, that does not receive sewage, industrial, or agricultural pollution, and that can be controlled through ownership or watershed rules and regulations would be preferred to a stream or creek, the pollution of which cannot from a practical standpoint be controlled. There are many situations where there is no practical alternative to the use of polluted streams for water supply. In such cases, carefully designed water-treatment plants providing multiple barriers must be provided.



Well at .... in .... County of ....
Name of place City, village or town

Owner .... P.O. Address ....

Depth of well .... ft Diameter .... in. Yield .... gpm Was well disinfected? .... yes or no

Amt. of casing above ground .... in. Below ground .... ft Well seal .... cement grout

Draw a well diagram in the space provided below and show the depth and type of casing, the well seal, kind and thickness of formations penetrated, water-bearing formations, diameter of drill holes with dotted lines, and casing(s) with solid lines.

Well Diagram Diameter, in.		Depth in ft	Formations Penetrated Kind, thickness, and if water bearing
		Grade	
		25	
		50	
		75	
		100	
		150	
		200	
		250	

Remarks

Type of well ....
Drilling method ....
Was well dynamited?

Pumping Tests

Details	#1	#2	#3
Static water level, in feet below grade			
Pumping rate in gpm			
Pumping level in feet below grade			
Duration of test, in hours			

Water at end of test:
Clear Cloudy Turbid
Recommended depth of pump in well, ft below grade Capacity .... gpm

Wells in sand & gravel:
Sand Eff. size .... mm
Unif. Coef. ....
Length of screen .... ft
Diam. of screen .... in.
Type of screen
Screen openings .... x ....

Comments:

Show cross-section of well & formations penetrated above. Draw a sketch of the property on the back of this sheet locating the well and sewage disposal systems within 200 ft, also land uses.

Drilling started .... Completed ....
Well driller ....
Signature

FIGURE 1.4 Well driller's log and report. *Well yield* is the volume of water per unit of time, such as gallons per minute, discharged from a well either by pumping to a stabilized drawdown or by free flow. The *specific capacity* of a well is the yield at a stabilized drawdown and given pumping rate, expressed as gallons per minute per foot of drawdown. Chalked tape, electric probe, or known length of air line is used with pressure gauge. Test run is usually 4 to 8 hours for small wells; 24 to 72 hours for wells serving the public, or for 6 hours at a stabilized drawdown when pumping at 1.5 times the design pumping rate.

TABLE 1.15 Standards for Construction of Wells[a]

Water-Bearing Formation	Overburden	Oversize Drill Hole		Cased Portion
		Diameter	Depth[b]	
1. Sand or gravel	Unconsolidated caving material; sand or sand and gravel	None required	None	2 in. minimum, 5 in. or more preferred
2. Sand or gravel	Clay, hardpan, silt, or similar material to depth of more than 20 ft	Casing size plus 4 in.	Minimum 20 ft	2 in. maximum, 5 in. or more preferred
3. Sand or gravel	Clay, hardpan, silt, or similar material containing layers of sand or gravel within 15 ft of ground surface	Casing size plus 4 in.	Minimum 20 ft	2 in. minimum, 5 in or more preferred
4. Sand or gravel	Creviced or fractured rock, such as limestone, granite, quartzite	Casing size plus 4 in.	Through rock formation	4 in. minimum
5. Creviced, shattered, or otherwise fractured limestone, granite, quartzite, or similar rock types	Unconsolidated caving material, chiefly sand or sand and gravel to a depth of 40 ft or more and extending at least 2000 ft in all directions from the well site	None required	None required	6 in. minimum

Well Diameter					
Uncased Portion	Well Screen Diameter[c]	Minimum Casing Length or Depth[b]	Liner Diameter (If Required)	Construction Conditions[b]	Miscellaneous Requirements
Does not apply	2 ft minimum	20 ft minimum; but 5 ft below pumping level[d]	2 in. minimum		
Does not apply	2 ft minimum	5 ft below pumping level[d]	2 in. minimum	Upper drill hole shall be kept at least one-third filled with clay slurry while driving permanent casing; after casing is in permanent position annular space shall be filled with clay slurry or cement grout.	An adequate well screen shall be provided where necessary to permit pumping sand-free water from the well.
Does not apply	2 ft minimum	5 ft below pumping level[d]	2 in. minimum	Annular space around casing shall be filled with cement grout.	
Does not apply	2 in. minimum	5 ft below overburden of rock	2 in. minimum	Annular space around casing shall be filled with cement grout.	
6 in. preferred	Does not apply	Through caving overburden	4 in. minimum	Casing shall be firmly seated in the rock.	

(*continues*)

TABLE 1.15 (*continued*)

Water-Bearing Formation	Overburden	Oversize Drill Hole Diameter	Oversize Drill Hole Depth[b]	Cased Portion
6. Creviced, shattered, or otherwise fractured limestone, granite, quartzite, or similar rock types	Clay, hardpan, shale, or similar material to a depth of 40 ft or more and extending at least 2000 ft in all directions from well site	Casing size plus 4 in.	Minimum 20 ft	6 in. minimum
7. Creviced, shattered, or otherwise fractured limestone, granite, quartzite, or similar rock	Unconsolidated materials to a depth of less than 40 ft and extending at least 2,000 ft in all directions	Casing size plus 4 in.	Minimum 40 ft	6 in. minimum
8. Sandstone	Any material except creviced rock to a depth of 25 ft or more	Casing size plus 4 in.	15 ft into firm sandstone or to 30 ft depth, whichever is greater	4 in. minimum
9. Sandstone	Mixed deposits mainly sand and gravel, to a depth of 25 ft or more	None required	None required	4 in. minimum

Well Diameter					
Uncased Portion	Well Screen Diameter[c]	Minimum Casing Length or Depth[b]	Liner Diameter (If Required)	Construction Conditions[b]	Miscellaneous Requirements
6 in. preferred	Does not apply	Through overburden	4 in. minimum	Annular space around casing shall be grouted. Casing shall be firmly seated in rock.	
6 in. preferred	Does not apply	40 ft minimum	4 in. minimum	Casing shall be firmly seated in rock. Annular space around casing shall be grouted.	If grout is placed through casing pipe and forced into annular space from the bottom of the casing, the oversize drill hole may be only 2 in. larger than the casing pipe.
4 in. preferred		Same as oversize drill hole or greater	2 in. minimum	Annular space around casing shall be grouted. Casing shall be firmly seated in sandstone.	Pipe 2 in. smaller than the drill hole and liner pipe 2 in. smaller than casing shall be assembled without couplings.
4 in. preferred		Through overburden into firm sandstone	2 in. minimum	Casing shall be effectively seated into firm sandstone.	

(*continues*)

TABLE 1.15 (*continued*)

Water-Bearing Formation	Overburden	Oversize Drill Hole: Diameter	Oversize Drill Hole: Depth[b]	Cased Portion
10. Sandstone	Clay, hardpan, or shale to a depth of 25 ft or more	Casing size plus 4 in.	Minimum 20 ft	4 in. minimum

Well Diameter					
Uncased Portion	Well Screen Diameter[c]	Minimum Casing Length or Depth[b]	Liner Diameter (If Required)	Construction Conditions[b]	Miscellaneous Requirements
4 in. preferred		Through overburden into sandstone	2 in. minimum	Casing shall be effectively seated into firm sandstone. Oversized drill hole shall be kept at least one-third filled with clay slurry while driving permanent casing; after the casing is in the permanent position, annular space shall be filled with clay slurry or cement grout.	Pipe 2 in. smaller than the oversize drill hole and liner pipe 2 in. smaller than casing shall be assembled without couplings.
	2 in. minimum, if well screen required to permit pumping sand-free water from partially cemented sandstone				

(*continues*)

TABLE 1.15 (*continued*)

		Oversize Drill Hole		
Water-Bearing Formation	Overburden	Diameter	Depth[b]	Cased Portion
11. Sandstone	Creviced rock at variable depth	Casing size plus 4 in.	15 ft or more into firm sandstone	6 in. minimum

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Note: For wells in creviced, shattered, or otherwise fractured limestone, granite, quartzite, or similar rock in which the overburden is less than 40 ft and extends less than 2,000 ft in all directions and no other practical acceptable water supply is available, the well construction described in line 7 of this table is applicable.

[a] Requirements for the proper construction of wells vary with the character of subsurface formations, and provisions applicable under all circumstances cannot be fixed. The construction details of this table may be adjusted, as conditions warrant, under the procedure provided by the Health Department and in the Note above.

[b] In the case of a flowing artesian well, the annular space between the soil and rock and the well casing shall be tightly sealed with cement grout from within 5 ft of the top of the aquifer to the ground surface in accordance with good construction practice.

[c] These diameters shall be applicable in circumstances where the use of perforated casing is deemed practicable. Well points commonly designated in the trade as $1\frac{1}{4}$-in. pipe shall be considered as being 2 ft nominal diameter well screens for purposes of these regulations.

[d] As used herein, the term *pumping level* shall refer to the lowest elevation of the surface of the water in a well during pumping, determined to the best knowledge of the water well contractor, taking into consideration usual seasonal fluctuations in the static water level and drawdown level.

Source: Recommended State Legislation and Regulations, Public Health Service, Department of Health, Education, and Welfare, Washington, DC, July 1965.

Well Diameter					
Uncased Portion	Well Screen Diameter[c]	Minimum Casing Length or Depth[b]	Liner Diameter (If Required)	Construction Conditions[b]	Miscellaneous Requirements
6 in. preferred		15 ft into firm sandstone	4 in. minimum	Annular space around casing shall be filled with cement grout.	If grout is placed through casing pipe and forced into annular space from the bottom of the casing, the oversize drill hole may be only 2 in. larger than the casing pipe. Pipe 2 in. smaller than the drill hole and liner pipe 2 in. smaller than casing shall be assembled without couplings.

Groundwater

About one-half of the U.S. population depends on groundwater for drinking and domestic purposes; 98 percent of the rural population is almost entirely dependent on groundwater. Some 43.5 million people are served by individual, on-site well-water systems (2000 USGS). These are not protected or regulated under the Safe Drinking Water Act. In view of this, protection of our groundwater resources must receive the highest priority. Elimination of groundwater pollution and protection of aquifers and their drainage areas by land-use and other controls require state and local regulations and enforcement.

It is estimated that there is more than 100 times more water stored underground than in all the surface streams, lakes, and rivers. Protection and development of groundwater sources can significantly help meet the increasing water needs. Exploration techniques include use of data from USGS and state agencies, previous studies, existing well logs, gains or losses in stream flow, hydrogeologic mapping using aerial photographs, surface resistivity surveys electromagnetic induction surveys or other geophysical prospecting, and exploratory test wells.

A technique for well location called *fracture-trace mapping* is reported to be a highly effective method for increasing the ratio of successful to unsuccessful well-water drilling operations and to greatly improve water yields (up to 50 times). Aerial photographs give the skilled hydrogeologist clues of the presence of a zone of fractures underneath the earth's surface. Clues are abrupt changes in the alignment of valleys, the presence of taller or more lush vegetation, the alignment of sink holes or other depressions in the surface, or the existence of shallow, longitudinal depressions in the surface overtop of the fracture zone. The soil over fracture zones is often wetter and, hence, shows up darker in recently plowed fields. The aerial photograph survey is then followed by a field investigation and actual ground location of the fractures and potential well-drilling sites.[140]

It has been suggested that all groundwater supplies be chlorinated. Exceptions may be properly located, constructed, and protected wells *not* in limestone or other channeled or fractured rock and where the highest water table level is at least 10 feet below ground level; where sources of pollution are more than 5,000 feet from the well; and where there is a satisfactory microbiological history. Other criteria include soil permeability, rate and direction of groundwater flow, and underground drainage area to the well. Chlorination should be considered a factor of safety and not reason to permit poor well construction and protection.

Dug Well

A dug well is one usually excavated by hand, although it may be dug by mechanical equipment. It may be 3 to 6 feet in diameter and 15 to 35 feet deep, depending on where the water-bearing formation or groundwater table is encountered. Wider and deeper wells are less common. Hand pumps over wells and pump lines entering wells should form watertight connections, as shown in Figure 1.5 and Figure 1.6. Since dug wells have a relatively large diameter, they have large storage capacity. The level of the water in dug wells will lower at times of

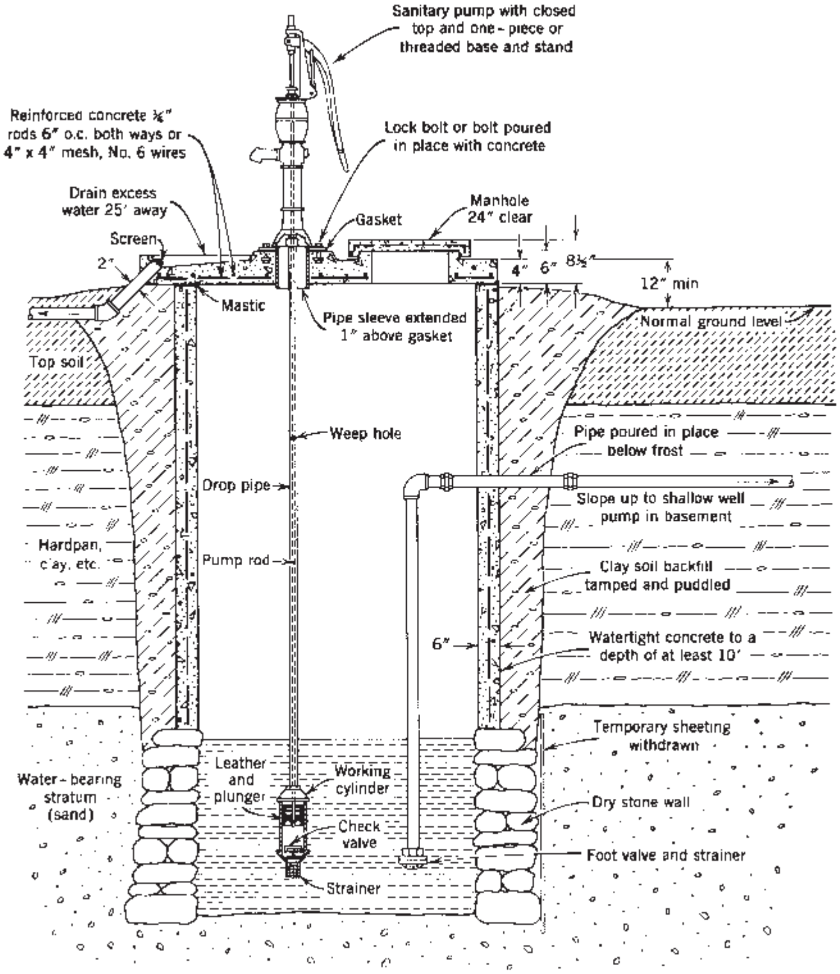


FIGURE 1.5 A properly developed dug well.

drought and the well may go dry. Dug wells are not usually dependable sources of water supply, particularly where modern plumbing is provided. In some areas, properly developed dug wells provide an adequate and satisfactory water supply. However, dug wells are susceptible to contamination deposited on or naturally present in the soil when subjected to heavy rains, particularly if improperly constructed. This potential hazard also applies to shallow bored, driven, and jetted wells. Water quality can be expected to change significantly.

Bored Well

A bored well is constructed with a hand- or machine-driven auger. Bored wells vary in diameter from 2 to 30 inches and in depth from 25 to 60 feet. A casing

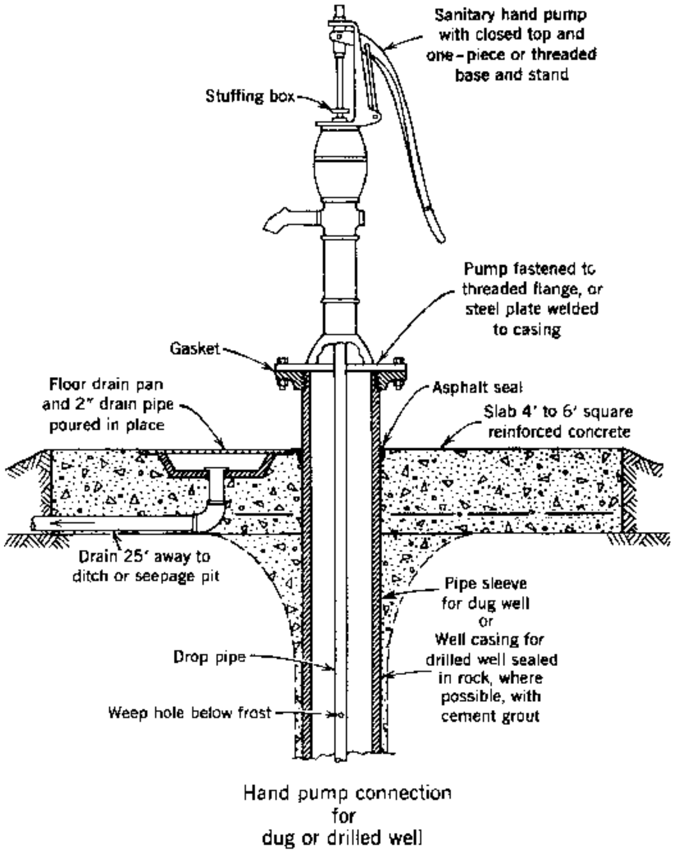


FIGURE 1.6 Sanitary hand pump and well attachment. Place 2 feet of gravel under slab where frost is expected.

of concrete pipe, vitrified clay pipe, metal pipe, or plastic pipe is necessary to prevent the relatively soft formation penetrated from caving into the well. Bored wells have characteristics similar to dug wells in that they have small yields, are easily polluted, and are affected by droughts.

Driven and Jetted Well

These types of wells consist of a well point with a screen attached, or a screen with the bottom open, which is driven or jetted into a water-bearing formation found at a comparatively shallow depth. A series of pipe lengths are attached to the point or screen as it is forced into position. The driven well is constructed by driving the well point, preferably through at least 10 to 20 feet of casing, with the aid of a maul or sledge, pneumatic tamper, sheet pile driver, drive monkey, hand-operated driver, or similar equipment. In many instances, the casing is omitted, but then less protection is afforded the driven well, which also serves as the pump suction line. The jetted well is constructed by directing a stream of water at the bottom of the open screen, thereby loosening and flushing the soil up the casing to the surface as the screen is lowered. Driven wells are commonly between 1-1/4 and 2 inches in diameter and less than 50 feet in depth; jetted wells may be 2 to 12 inches in diameter and up to 100 feet deep, although larger and deeper wells can be constructed. In the small-diameter wells, a shallow well hand or mechanical suction pump is connected directly to the well. Large-diameter driven wells facilitate installation of the pump cylinder close to or below the water surface in the well at greater depth, in which case the hand pump must be located directly over the well. In all cases, however, care must be taken to see that the top of the well is tightly capped, the concrete pump platform extends 2 or 3 feet around the well pipe or casing, and the annular space between the well casing and drop pipe(s) is tightly sealed. This is necessary to prevent the entrance of unpurified water or other pollution from close to the surface.

A radial well is a combination dug-and-driven well in which horizontally driven well collectors radiate out from a central sump or core and penetrate into a water-bearing stratum.

Drilled Well

Studies have shown that, in general, drilled wells are superior to dug, bored, or driven wells and springs. But there are some exceptions. Drilled wells are less likely to become contaminated and are usually more dependable sources of water. When a well is drilled, a hole is made in the ground, usually with a percussion (cable tool) or rotary (air or mud) drilling machine. Drilled wells are usually 4 to 12 inches in diameter or larger and may reach 750 to 1,000 feet in depth or more. Test wells are usually 2 to 5 inches in diameter with a steel casing. A steel or wrought-iron casing is lowered as the well is drilled to prevent the hole from caving in and to seal off water of doubtful quality. Special plastic pipe is also used if approved. Lengths of casing should be threaded and coupled or properly field welded. The drill hole must, of course, be larger than the casing, thereby leaving an irregular space around the outside length of the casing. Unless this space or channel is closed by cement grout or naturally by formations that conform to the casing almost as soon as it is placed, pollution from the surface or crevices close to the surface or from polluted formations penetrated will flow down the side of the casing and into the water source. Water can also move up and down this annular space in an artesian well and as the groundwater and pumping water level changes.

The required well diameter is usually determined by the size of the discharge piping, fittings, pump, and motor placed inside the well casing. In general, for well yields of less than 100 gpm, a 6-inch-inside-diameter casing should be used; for 75 to 175 gpm an 8-inch casing; for 150 to 400 gpm a 10-inch casing; for 350 to 650 gpm a 12-inch casing; for 600 to 900 gpm a 14-inch-outside-diameter casing; for 850 to 1,300 gpm a 16-inch casing; for 1,200 to 1,800 gpm a 20-inch casing; and for 1,600 to 3,000 gpm a 24-inch casing.[141] Doubling the diameter of a casing increases the yield up to only 10 to 12 percent.

When the source of water is water-bearing sand and gravel, a gravel well or gravel-packed well with screen may be constructed. Such a well will usually yield more water than the ordinary drilled well with a screen of the same diameter and with the same drawdown. A slotted or perforated casing in a water-bearing sand will yield only a fraction of the water obtainable through the use of a proper screen selected for the water-bearing material. On completion, the well should be developed and tested, as noted previously. A completed well driller's log should be provided to the owner on each well drilled. See Figure 1.4.

Only water well casing of clean steel or wrought iron should be used. Plastic pipe may be permitted. Used pipe is unsatisfactory. Standards for well casing are available from the American Society for Testing Materials, the American Iron and Steel Institute, and state health or environmental protection agencies.

Extending the casing at least 5 feet below the pumping water level in the well—or if the well is less than 30 feet deep, 10 feet below the pumping level—will afford an additional measure of protection. In this way, the water is drawn from a depth that is less likely to be contaminated. In some sand and gravel areas, extending the casing 5 to 10 feet below the pumping level may shut off the water-bearing sand or gravel. A lesser casing depth would then be indicated, but in no instance should the casing be less than 10 feet, provided sources of pollution are remote and provision is made for chlorination. The recommended depth of casing, cement grouting, and need for double-casing construction or the equivalent are given in Table 1.15.

A vent is necessary on a well because, if not vented, the fluctuation in the water level will cause a change in air pressure above and below atmospheric pressure in a well, resulting in the drawing in of contaminated water from around the pump base over the well or from around the casing if not properly sealed. Reduced pressure in the well will also increase lift or total head and reduce volume of water pumped.

It must be remembered that well construction is a very specialized field. Most well drillers are desirous of doing a proper job, for they know that a good well is their best advertisement. However, in the absence of a state or local law dealing with well construction, the enforcement of standards, and the licensing of well drillers, price alone frequently determines the type of well constructed. Individuals proposing to have wells drilled should therefore carefully analyze bids received. Such matters as water quality, well diameter, type and length of casing, minimum well yield, type of pump and sanitary seal where the pump line(s) passes through the casing, provision of a satisfactory well log, method used to seal off undesirable formations and cement grouting of the well, plans to pump the well until clear, and disinfection following construction should all be taken into consideration. See Figures 1.6 through 1.12.

Recommended water well protection and construction practices and standards are given in this text. More detailed information, including well construction and development, contracts, and specifications, is available in federal, state, and other

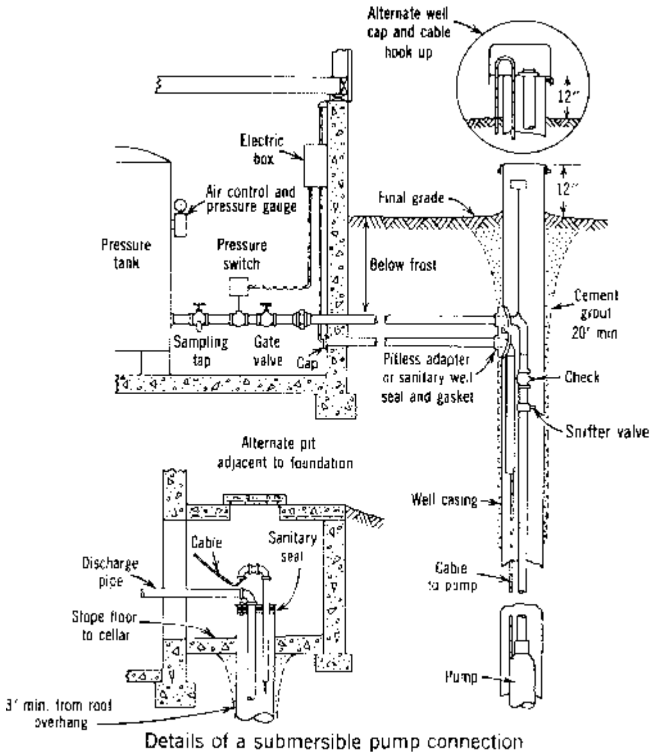


FIGURE 1.7 Sanitary well caps and seal and submersible pump connection.

publications.[142] A hydrogeologist or professional engineer can help assure proper location, construction, and development of a well, particularly for a public water supply. It has been estimated that the radius of the cone of depression of a well in fine sand is 100 to 300 feet, in coarse sand 600 to 1,000 feet, and in gravel 1,000 to 2,000 feet. In a consolidated formation, determination of the radius of the cone of depression requires a careful hydrogeological analysis. Remember, the cheapest well is not necessarily the best buy.

Well Development

Practically all well-drilling methods, and especially the rotary drill method, cause smearing and compaction or cementing of clay, mud, and fine material on the bore hole wall and in the crevices of consolidated formations penetrated. This will reduce the sidewall flow of water into the well and, hence, the well yield. Various methods are used to remove adhering mud, clay, and fines and to develop a well to its full capacity. These include pumping, surging (valved surge device, solid surge device, pumping with surge device, air surge), and fracturing (explosives, high-pressure jetting, backwashing). Adding a polyphosphate or a nonfoaming

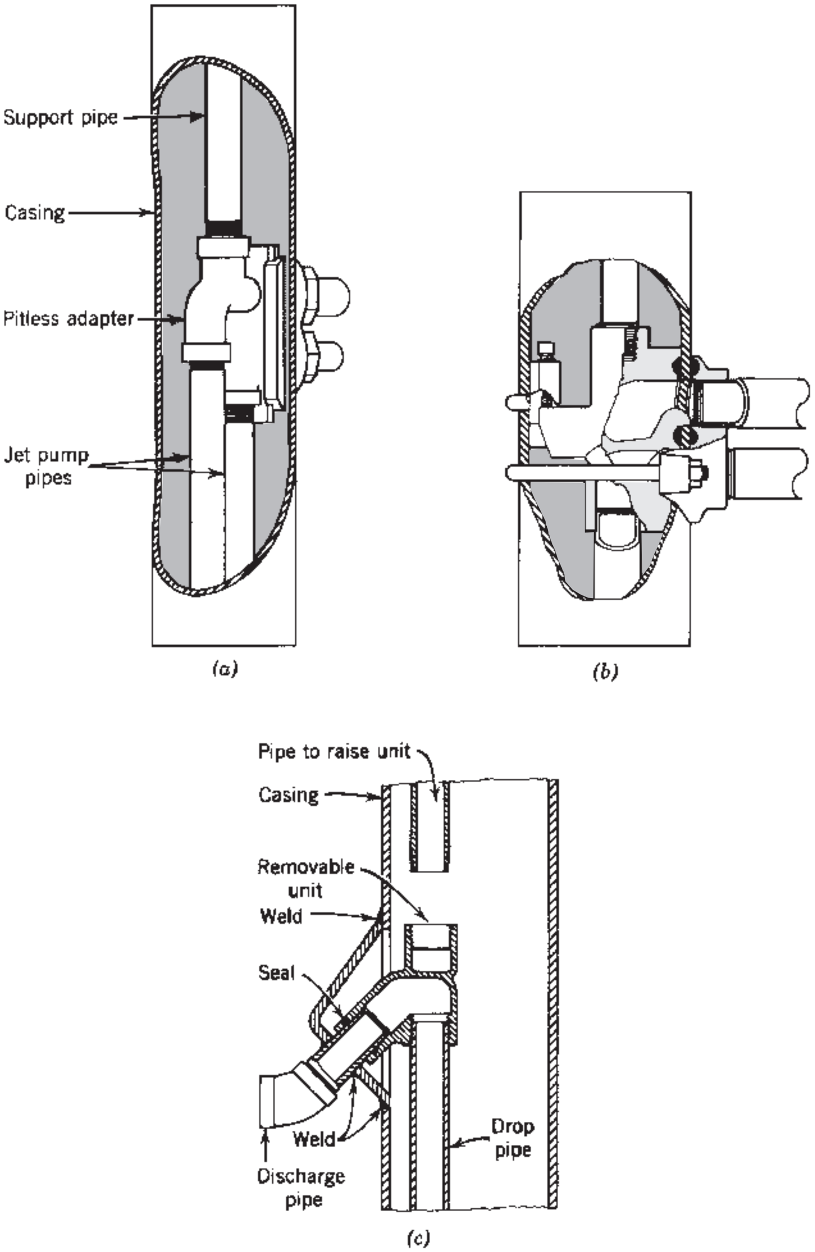


FIGURE 1.8 Pitless adapters. ((*a*) Courtesy Martin Manufacturing Co., Ramsey, NJ. (*b*) Courtesy Williams Products Co., Joliet, IL. (*c*) Courtesy Herb Maass Service, Milwaukee, WI.)

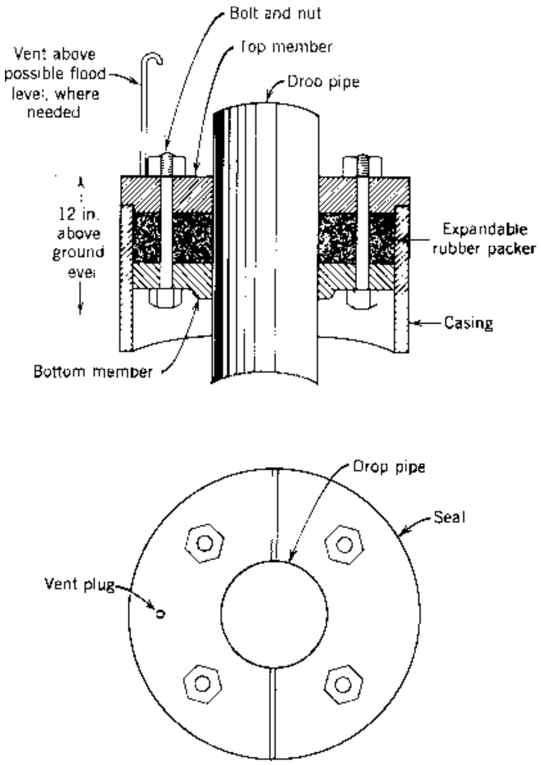
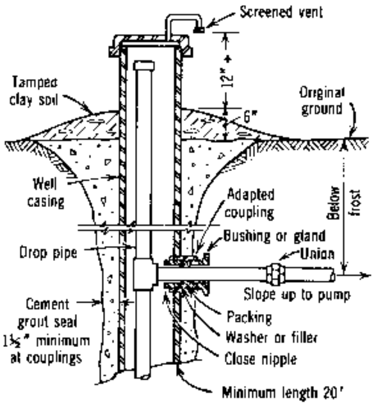


FIGURE 1.9 Sanitary expansion well cap.



Shallow well or submersible pump underground connection

FIGURE 1.10 Improved well seal.

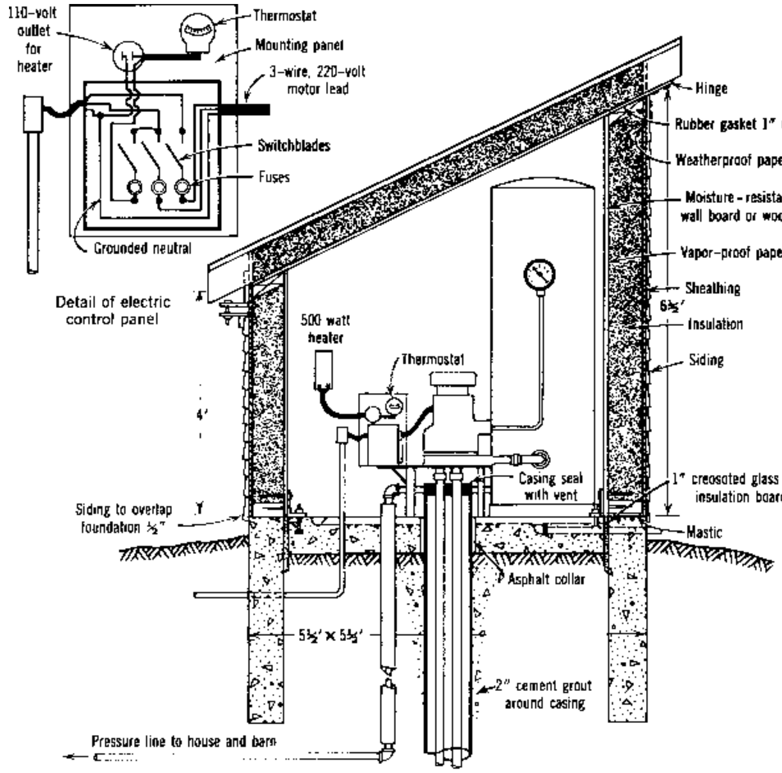


FIGURE 1.11 Insulated pumphouse. (*Source: Sewage Disposal and Water Systems on the Farm*, Extension Bulletin 247, University of Minnesota Extension Service, revised 1956. Reproduced with permission.)

detergent can also aid in removing adhering materials. The well development operation is continued until the discharge becomes practically clear of sand (5 ppm or less). Following development, the well should be tested to determine the dependable well yield. The well is then disinfected and the log completed.

Grouting

One of the most common reasons for contamination of wells drilled through rock, clay, or hardpan is failure to properly seal the annular space around the well casing. A proper seal is needed to prevent water movement between aquifers, protect the aquifers, and prevent entry of contaminated water from the surface or near the surface.

A contaminated well supply causes the homeowner or municipality considerable inconvenience and extra expense, for it is difficult to seal off contamination after the well is drilled. In some cases, the only practical answer is to build a new well.

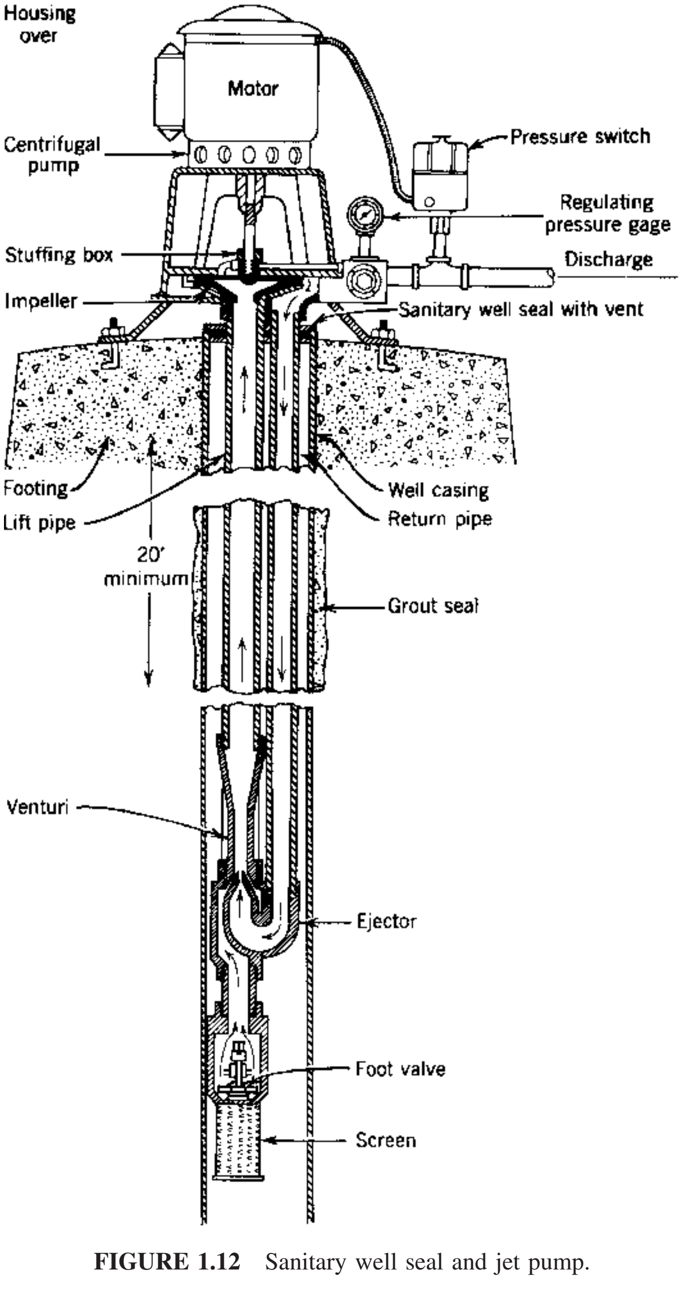


FIGURE 1.12 Sanitary well seal and jet pump.

Proper *cement grouting* of the space between the drill hole and well casing, the annulus, where the overburden over the water-bearing formation is clay, hardpan, or rock, can prevent this common cause of contamination. (See Table 1.15.)

There are many ways to seal well casings. The best material is neat cement grout.* However, to be effective, the grout must be properly prepared (a proper mixture is 5-1/2 to 6 gal of clean water to a bag of cement), pumped as one continuous mass, and placed upward from the bottom of the space to be grouted. An additive such as bentonite may be used to minimize shrinkage and increase fluidity, if approved.

The clear annular space around the outside of the casing couplings and the drill hole must be at least 1-1/2 in. on all sides to prevent bridging of the grout. Guides must be welded to the casing.

Cement grouting of a well casing along its entire length of 50 to 100 feet or more is good practice but expensive for the average farm or rural dwelling. An alternative is grouting to at least 20 feet below ground level. This provides protection for most installations, except in limestone and fractured formations. It also protects the casing from corrosion.

For a 6-inch-diameter well, a 10-inch hole is drilled, if 6-inch welded pipe is used, to at least 20 feet or to solid rock if the rock is deeper than 20 feet. If 6-inch coupled pipe is used, a 12-inch hole will be required. From this depth the 6-inch hole is drilled deeper until it reaches a satisfactory water supply. A temporary outer casing, carried down to rock, prevents cave-in until the cement grout is placed.

Upon completion of the well, the annular space between the 6-inch casing and temporary casing or drill hole is filled from the bottom up to the grade with cement grout. The temporary pipe is withdrawn as the cement grout is placed—it is not practical to pull the casing after all the grout is in position.

The extra cost of the temporary casing and larger drill hole is small compared to the protection obtained. The casing can be reused as often as needed. In view of this, well drillers who are not equipped should consider adding larger casing and equipment to their apparatus.

A temporary casing or larger drill hole and cement grouting are not required where the entire earth overburden is 40 feet or more of silt or sand and gravel, which immediately close in on the total length of casing to form a seal around the casing; however, this condition is not common.

Drilled wells serving public places are usually constructed and cement grouted as explained in Table 1.15.

In some areas, limestone and shale beneath a shallow overburden represent the only source of water. Acceptance of a well in shale or limestone might be conditioned on an extended observation period to determine the sanitary quality of the water. Continuous chlorination should be required on satisfactory supplies serving the public and should be recommended to private individuals. However,

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*Sand–cement grout, two parts sand to one part Portland cement by weight, with not more than 6 gal of water per sack of cement, may also be used. The curing time for neat cement is 72 hr; for high early strength cement, at least 36 hr.

chlorination should not be relied on to make a heavily contaminated well-water supply satisfactory. Such supplies should be abandoned and filled in with concrete or puddled clay unless the source of contamination can be eliminated.

Well drillers may have other sealing methods suitable for particular local conditions, but the methods just described utilizing a neat cement or sand-cement grout will give reasonably dependable assurance that an effective seal is provided, whereas this cannot be said of some of the other methods used. Driving the casing, a lead packer, drive shoe, rubber sleeves, and similar devices do not provide reliable annular space seals for the length of the casing.

Well Contamination — Cause and Removal

Well-water supplies are all too often improperly constructed, protected, or located, with the result that microbiological examinations show the water to be contaminated. Under such conditions, all water used for drinking or culinary purposes should first be boiled or adequately treated. Boiling will not remove chemical contaminants other than volatiles; treatment may remove some. If practical, abandonment of the well and connection to a public water supply would be the best solution. A second alternative would be investigation to find and remove the cause of pollution; however, if the aquifer is badly polluted, this may take considerable time. A third choice would be a new, properly constructed and located drilled well in a clean aquifer. See “Travel of Pollution through the Ground,” earlier in this chapter.

When a well shows the presence of bacterial contamination, it is usually due to one or more of four probable causes: lack of or improper disinfection of a well following repair or construction; failure to seal the annular space between the drill hole and the outside of the casing; failure to provide a tight sanitary seal at the place where the pump line(s) passes through the casing; and wastewater pollution of the well through polluted strata or a fissured or channeled formation. On some occasions, the casing is found to be only a few feet in length and completely inadequate. Chemical contamination usually means the aquifer has been polluted.

If a new well is constructed or if repairs are made to the well, pump, or piping, contamination from the work is probable. The well, pump, storage tank, and piping should be disinfected, as explained in this chapter.

If a sewage disposal system is suspected of contamination, a dye such as water-soluble sodium or potassium fluorescein or ordinary salt can be used as a tracer. A solution flushed into the disposal system or suspected source may appear in the well water within 12 to 24 hours. It can be detected by sight, taste, or analysis if a connection exists. Samples should be collected every few hours and set aside for comparison. If the connection is indirect, fluoroscopic or chemical examination for the dye or chlorides is more sensitive. One part of fluorescein in 10 to 40 million parts of water is visible to the naked eye, and in 10 billion parts if viewed in a long glass tube or if concentrated in the laboratory. The chlorides in the well before adding salt should, of course, be known. Where chloride determinations are routinely made on water samples, sewage pollution may be apparent without making the salt test. Dye is not decolorized by passage through sand, gravel, or manure; it is slightly decomposed by calcareous soils and entirely decolorized by peaty formations and free acids, except carbonic acid.[143] A copper sulfate solution (300 mg/1), nonpathogenic bacteria and spores, radionuclides, strong electrolytes, and nonfluorescent dyes have also been used. Dyes include congo red, malachite green, rhodamine, pyranine, and photine.[144]

If the cause of pollution is suspected to be an underground seal where the pump line(s) passes through the side of the casing, a dye or salt solution or even plain water can be poured around the casing. Samples of the water can be collected for visual or taste test or chemical examination. The seal might also be excavated for inspection. Where the upper part of the casing can be inspected, a mirror or strong light can be used to direct a light beam inside the casing to see if water is entering the well from close to the surface. Sometimes it is possible to hear the water dripping into the well. Inspection of the top of the well will also show if the top of the casing is provided with a sanitary seal and whether the well is subject to flooding. See Figures 1.7 to 1.12.

The path of pollution entry can also be holes in the side of the casing, channels along the length of the casing leading to the well source, crevices or channels connecting surface pollution with the water-bearing stratum, or the annular space around the casing. A solution of dye, salt, or plain water can be used to trace the pollution, as previously explained.

The steps taken to provide a satisfactory water supply would depend on the results of the investigation. If a sanitary seal is needed at the top or side of the casing where the pump lines pass through, then the solution is relatively simple. On the other hand, an unsealed annular space is more difficult to correct. A competent well driller could be engaged to investigate the possibility of grouting the annular space and installing an inner casing or a new casing carefully sealed in solid rock. If the casing is found tight, it would be assumed that pollution is finding its way into the water-bearing stratum through sewage-saturated soil or creviced or channeled rock at a greater depth. It is sometimes possible, but costly, to seal off the polluted stratum and, if necessary, drill deeper.

Once a stratum is contaminated, it is very difficult to prevent future pollution of the well unless all water from such a stratum is effectively sealed off. Moving the offending sewage disposal system to a safe distance or replacing a leaking oil or gasoline tank is possible, but evidence of the pollution may persist for some time.

If a dug well shows evidence of contamination, the well sidewalls may be found to consist of stone or brick lining, which is far from being watertight. In such cases, the upper 6 to 10 feet should be removed and replaced with a poured concrete lining and platform. As an alternative, a concrete collar 6 to 12 inches thick, 6 to 10 feet deep could be poured around the *outside* of the stone or brick lining (see Figure 1.5). Take safety precautions (see *Safety* in Index).

Chemical contamination of a well and the groundwater aquifer can result from spills, leaking gasoline and oil tanks, or improper disposal of chemical wastes such as by dumping—on the ground in landfills—lagooning, or similar methods. Gasoline and oil tanks typically have a useful life of about 20 years, depending on the type of soils and tank coatings. Since many tanks have been in the ground 20 to 30 years or longer, their integrity must be uncertain and they are probably leaking to a greater or lesser degree. New tanks are not necessarily immune from leakage. If not already being done, oil, gasoline, and other buried tanks containing hazardous chemicals should be tested periodically and, of course, at the first sign of leakage promptly replaced with approved tanks. The number of tanks, surreptitious dumpings, discharges to leaching pits, and other improper disposals make control a formidable task. This subject is discussed further in this chapter; see "Groundwater Pollution Hazard" and "Travel of Pollution through the Ground."

Unless all the sources of pollution can be found and removed, it is recommended that the well be abandoned and filled with neat cement grout, puddled clay, or concrete to prevent the pollution from traveling to other aquifers or wells. In some special cases and under controlled conditions, use of a slightly contaminated water supply may be permitted provided approved treatment facilities are installed. Such equipment is expensive and requires constant attention. If a public water supply is not available and a new well is drilled, it should be located and constructed as previously explained.

Spring

Springs are broadly classified as either rock springs or earth springs, depending on the source of water. To obtain satisfactory water, it is necessary to *find the source*, properly develop it, eliminate surface water, and prevent animals from gaining access to the spring area.

Protection and development of a source of water are shown in Figure 1.13. A combination of methods may also be possible under certain ground conditions and would yield a greater supply of water than either alone.

In all cases, the spring should be protected from surface-water pollution by constructing a deep diverting ditch or the equivalent above and around the spring. The spring and collecting basin should have a watertight top, preferably concrete, and water obtained by gravity flow or by means of a properly installed sanitary hand or mechanical pump. Access or inspection manholes, when provided, should be tightly fitted (as shown) and kept locked. Water from limestone or similar type channeled or fissured rock springs is not purified to any appreciable extent when traveling through the formation and hence may carry pollution from nearby or distant places. Under these circumstances, it is advisable to have periodic bacteriological examinations made and chlorinate the water.

Infiltration Gallery

An infiltration gallery consists of a system of porous, perforated, or open-joint pipe or other conduit draining to a receiving well. The pipe is surrounded by gravel and located in a porous formation such as sand and gravel below the water table. The collecting system should be located 20 feet or more from a lake or stream or under the bed of a stream or lake if installed under expert supervision. It

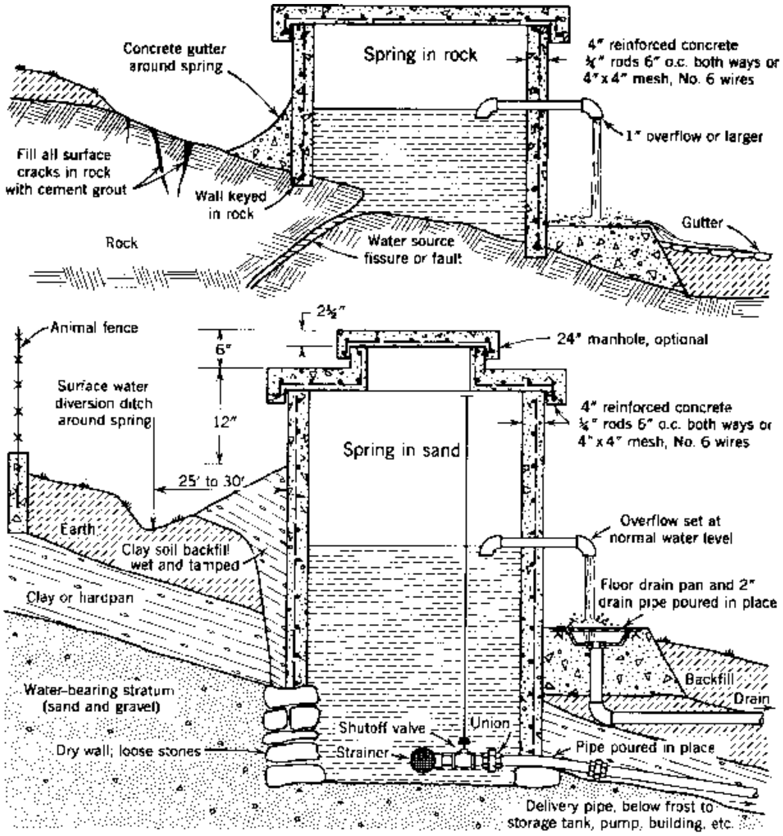

FIGURE 1.13 Properly constructed springs.

is sometimes found desirable, where possible, to intercept the flow of groundwater to the stream or lake. In such cases, a cofferdam, cutoff wall, or puddled clay dam is carefully placed between the collecting conduit and the lake or stream to form an impervious wall. It is not advisable to construct an infiltration gallery unless the water table is relatively stable and the water intercepted is free of pollution. The water-bearing strata should not contain cementing material or yield a very hard water, as it may clog the strata or cause incrustation of the pipe, thereby reducing the flow. An infiltration gallery is constructed similar to that shown in Figure 1.14. The depth of the collecting tile should be about 10 feet below the normal ground level, and below the lowest known water table, to assure a greater and more constant yield. An infiltration gallery may also be located at a shallow depth, above a highly mineralized groundwater, such as saline water, to collect the fresh or less mineralized water. An infiltration system consisting of horizontally perforated or porous radial collectors draining to a collecting well can also be designed and constructed where hydrogeological conditions are suitable, usually under a stream bed or lake, or where a thin water-bearing stratum exists. The

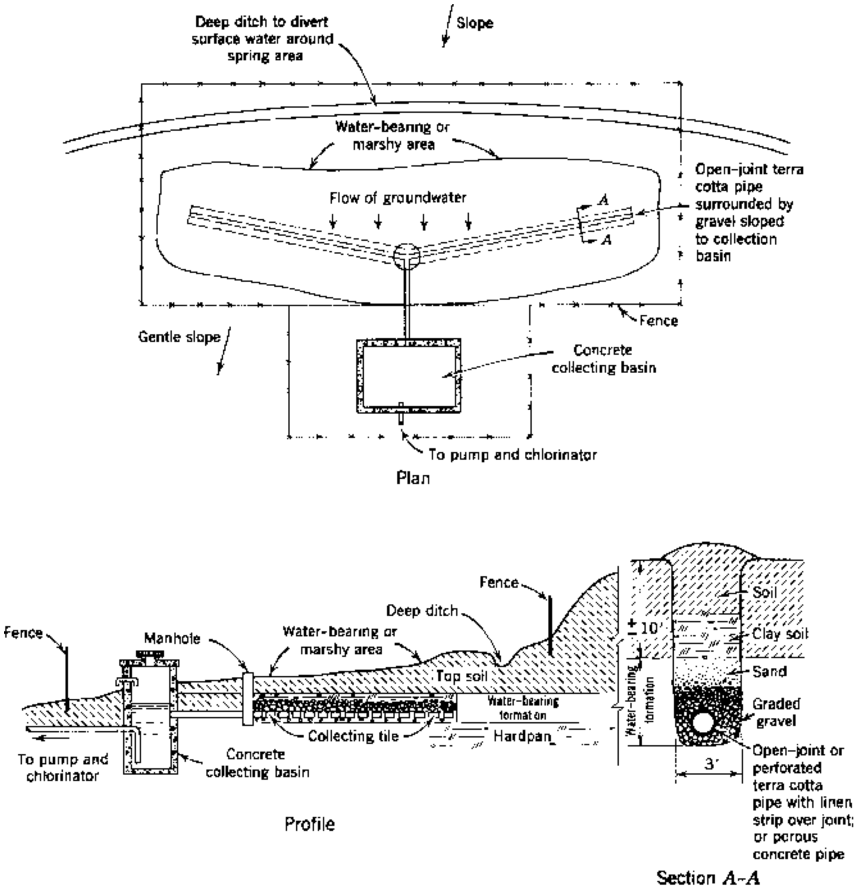

FIGURE 1.14 Development of a spring in a shallow water-bearing area.

infiltration area should be controlled and protected from pollution by sewage and other wastewater and animals. Water derived from infiltration galleries should, at the minimum, be given chlorination treatment.

Cistern

A cistern is a watertight tank in which rainwater collected from roof runoff or other catchment area is stored. When the quantity of groundwater or surface water is inadequate or the quality objectionable and where an adequate municipal water supply is not available, a cistern supply may be acceptable as a limited source of water. On the one hand, because rainwater is soft, little soap is needed when used for laundry purposes. On the other hand, rain will wash air pollutants, dust, dirt, bird and animal droppings, leaves, paint, and other material on the roof or in roofing materials or catchment area into the cistern unless special provision is made to bypass the first rainwater and filter the water. The bypass may consist of a simple manually or float-operated damper or switch placed in the leader drain. When in one position, all water will be diverted to a float control tank or to waste away from the building foundation and cistern; when in the other position, water will be run into the cistern. The filter will not remove chemical pollutants. If the water is to be used for drinking or food preparation, it should also be pointed out that because rainwater is soft and acidic, and therefore corrosive, hazardous concentrations of zinc from galvanized iron sheet roofing, gutters, and pipe and lead and copper from soldered copper pipe may also be released, in addition to cadmium.

The capacity of the cistern is determined by the size of the roof or catchment area, the probable water consumption, the maximum 24-hour rainfall, the average annual rainfall, and maximum length of dry periods. Suggested rainwater cistern sizes are shown in Figure 1.15. The cistern storage capacity given allows for a reserve supply, plus a possible heavy rainfall of 3-1/2 inches in 24 hours. The calculations assume that 25 percent of the precipitation is lost. Weather bureaus, the *World Almanac*, airports, water departments, and other agencies give rainfall figures for different parts of the country. Adjustment should therefore be made in

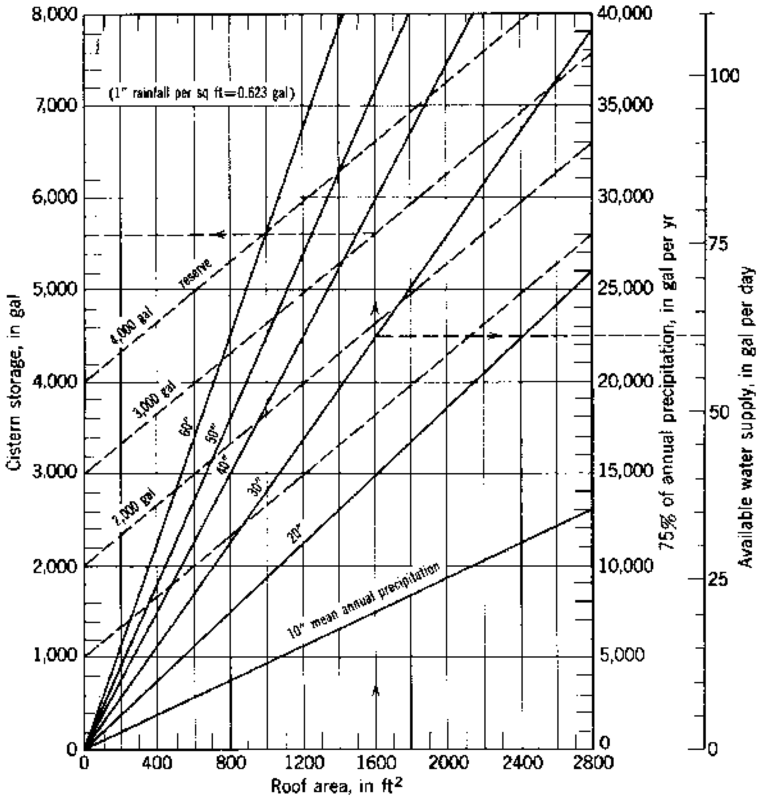

FIGURE 1.15 Suggested cistern storage capacity and available supply.

TABLE 1.16 Quantity and Type of Chlorine to Treat 1,000 gal of Clean Water at Rate of 1 mg/l

Chlorine Compound	Quantity
High test, 70% chlorine	1/5 oz or 1/4 heaping tablespoon
Chlorinated lime, 25% chlorine	1/2 oz or 1 heaping tablespoon
Sodium hypochlorite	
14% chlorine	1 oz
10% chlorine	1-1/3 oz
Bleach, 5-1/4 chlorine	2-3/5 oz

the required cistern capacity to fit local conditions. The cistern capacity will be determined largely by the volume of water one wishes to have available for some designated period of time, the total volume of which must be within the limits of the volume of water that the roof or catchment area and annual rainfall can safely yield. Monthly average rainfall data can be expected to depart from the true values by 50 percent or more on occasion. The drawing of a mass diagram is a more accurate method of estimating the storage capacity, since it is based on past actual rainfall in a given area.

It is recommended that the cistern water be treated after every rain with a chlorine compound of at least 5 mg/l chlorine. This may be accomplished by adding five times the quantities of chlorine shown in Table 1.16, mixed in 5 gallons of water to each 1,000 gallon of water in the cistern. A stack or tablet chlorinator and carbonate (limestone) contact tank on the inlet to the cistern is advised for disinfection and acidity neutralization. In areas affected by air pollution, fallout on the roof or catchment area will contribute chemical pollutants that may not be neutralized by limestone or chlorine treatment. Soft water flowing over galvanized iron roofs or through galvanized iron pipe or stored in galvanized tanks contains cadmium and zinc.[145]

Example With a roof area of 1,600 ft^2, in a location where the mean annual precipitation is 30 inches and it is desired to have a reserve supply of 3,000 gallon, the cistern storage capacity should be about 5,600 gallons. This should yield an average annual supply of about 62 gallons per day.

In some parts of the world, large natural catch basins are lined to collect rainwater. The water is settled and chlorinated before distribution. The amount of water is of course limited and may supplement groundwater, individual home cisterns, and desalinated water.

Domestic Well-Water Supplies — Special Problems*

Domestic well-water supply problems are discussed in this section.[146] The local health department and commercial water-conditioning companies may be of assistance to a homeowner.

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*This section is adapted from ref.146.

Hard Water Hard water makes it difficult to produce suds or rinse laundry, dishes, or food equipment. Water hardness is caused by dissolved calcium and magnesium bicarbonates, sulfates, and chlorides in well water. Pipes clog and after a time equipment and water heaters become coated with a hard mineral deposit, sometimes referred to as lime scale. A commercial zeolite or synthetic resin water softener is used to soften water. The media must be regenerated periodically and disinfected with chlorine to remove contamination after each regeneration. Softeners do not remove contamination in the water supply. A filter should be placed ahead of a softener if the water is turbid. See also “Water Softening,” in Chapter 2.

The sodium content of the water passing through a home water softener will be increased. Individuals who are on a sodium-restricted diet should advise their physician that they are using home-softened water since such water is a continual source of dietary sodium. A cold-water bypass line can be installed around the softener to supply drinking water and water for toilet flushing.

Turbidity or Muddiness This usually occurs in water from a pond, creek, or other surface source. Such water is polluted and requires coagulation, flocculation, sedimentation, filtration, and chlorination treatment. Wells sometimes become cloudy from cave-in or seepage from a clay or silt stratum but usually clear up with prolonged pumping. If the clay is in the colloidal state, coagulation, such as with aluminum sulfate (alum), is needed.

Sand filters can remove mud, dirt, leaves, foreign matter, and most bacteria, viruses, and protozoa if properly operated, but they may clog rapidly. Chlorination is also required to ensure destruction of pathogens. Charcoal, zeolite, or carbon filters are not suitable for this purpose, and, in addition, they clog. Iron and iron growths that sometimes cause turbidity in well water are discussed next. See also “Filtration”, in Chapter 2.

Iron and Manganese in Well Water Iron and manganese may be found in water from deep wells and springs. In high concentrations it causes a bitter taste in tea or coffee. When exposed to the air, iron, and manganese are oxidized and settle out. Red to brown or black (manganese) stains form on plumbing fixtures, equipment, and laundry. Chlorine bleach exacerbates the staining problem. Iron and manganese in solution (colloidal) form may be found in shallow wells, springs, and surface waters. In this form, the water has a faint red or black color.

A commercial home zeolite water softener removes 1.5 to 2.0 mg/l, and an iron removal filter removes up to 10 mg/l iron from well water devoid of oxygen. The water should *not* be aerated prior to zeolite filtration, as this will cause precipitation of oxidized (ferric) iron rather than the exchange of sodium by ferrous iron, which is washed out as ferrous chloride when regenerated. An iron removal filter will also remove some hydrogen sulfide. The water softener is regenerated with salt water. The iron removal filter is backwashed to remove the precipitated iron and regenerated with potassium permanganate. Since potassium permanganate is toxic, it must all be flushed out before the treated water is used. The controlled addition of a polyphosphate can keep 1.0 to 2.0 mg/l iron in solution, but, as with the zeolite softener, sodium is also added to the water. Heating of water to 140° to 150°F (60°–66°C) nullifies the effectiveness of polyphosphate.

With higher concentrations of iron, the water is chlorinated to oxidize the iron in solution and allowed a short contact period, but the water should then be filtered to remove the iron precipitate before it enters the distribution system. The pH of the water should be raised to above 7.0 if the water is acid; soda ash, added to the chlorine solution, is usually used for this purpose. Hydrogen peroxide or potassium permanganate will also oxidize the iron.

Another approach is to discharge the water to the air chamber of a pressure tank, or to a sprinkler over a cascade above a tank, but this will require double pumping. It is necessary to flush out the iron that settles in the tank and filter out the remainder. Air control is needed in a pressure tank. Air is admitted with the well water entering and air is vented from the tank. Manganese is also removed with iron treatment.

Injecting a chlorine solution into the water at its source, where possible, controls the growth of iron bacteria, if this is a problem. See also "Iron and Manganese Occurrence and Removal" and "Iron Bacteria Control," in Chapter 2. Before purchasing any equipment, seek expert advice and a proper demonstration should be sought.

Corrosive Water Water having a low pH or alkalinity and dissolved oxygen or carbon dioxide tends to be corrosive. Corrosive water dissolves metal, shortens the life of water tanks, discolors water, and clogs pipes. Iron corrosion causes rusty water; copper or brass pipe causes blue-green stains. Water can be made noncorrosive by passing it through a filter containing broken limestone, marble chips, or other acid neutralizers. The controlled addition of a polyphosphate, silicate, or soda ash to raise the water pH (commercial units are available) usually prevents metal from going into solution. The water remains clear and staining is prevented. However, bear in mind that a sodium polyphosphate would add sodium to the water, making it undesirable for individuals on a low-sodium diet. The use of low-lead solder (95:5 tinantimony solder), plastic pipe, maintenance of water temperature below 140°F (60°C), and a glass-lined hot water storage tank will minimize the problems associated with corrosion in home plumbing.

Taste and Odors Activated-carbon filters or cartridges are normally used to remove undesirable tastes and odors from domestic water supplies, but they do not remove microbiological contamination. Hydrogen sulfide in water causes a rotten-egg odor; corrosion of iron, steel, and copper; and black stains on laundry and crockery. It can also be eliminated by aeration and chlorination followed by filtration. An activated-carbon filter is not efficient. The activated carbon will have to be replaced when its capacity has been exhausted. Filtration alone, through a pressure filter containing a special synthetic resin, also removes up to 5 mg/l hydrogen sulfide in most cases. The water in question should be used to check the effectiveness of a process before any equipment is purchased. See also “Hydrogen Sulfide, Sources and Removal” in Chapter 2.

Detergents Detergents in water can be detected visually, by taste, or by laboratory examination. When some detergents exceed 1 mg/l, foam appears in a glass of water drawn from a faucet. Detergents themselves have not been shown to be harmful, but their presence is evidence that wastewater from one’s own sewage disposal system or from a neighbor’s system is entering the water supply source. In such circumstances, the sewage disposal system may be moved, a well constructed in a new area, or the well extended and sealed into a deeper water-bearing formation not subject to pollution. There is no guarantee that the new water-bearing formation will not be or become polluted later. The solution to this problem is connection to a public water supply and/or a public sewer. A granular activated-carbon (GAC) filter may be used to remove detergent, but its effectiveness and cost should first be demonstrated. See also “Methylene Blue Active Substances (MBAS),” previously in this chapter.

Salty Water In some parts of the country, salty water may be encountered. Since the salt water generally is overlain by fresh water, the lower part of the well in the salt water zone can be sealed off. But when this is done, the yield of the well is decreased.

Sometimes, waste salt water resulting from the backwashing of a home ion exchange water softener is discharged close to the well. Since salt water is not filtered out in seeping through the soil, it may find its way into the well. The best thing to do is to discharge the wastewater as far as possible and downgrade from the well or utilize a commercial water softener service. Salt water is corrosive; it will damage grass and plants and sterilize soil. Road salting or salt storage areas may also contribute to well pollution.

Special desalting units (using distillation, deionization, and reverse osmosis) are available for residential use, but they are of limited capacity and are relatively expensive, and pretreatment of the water may be needed. Complete information, including effectiveness with the water in question and annual cost, should be obtained before purchase. See “Desalination,” this chapter, for additional information.

Radon in Well Water See “Radon,” in this chapter.

Gasoline or Fuel Oil in Water See “Removal of Gasoline, Fuel Oil, and Other Organics in an Aquifer” and “Travel of Pollution through the Ground,” in Chapter 2.

Household Treatment Units (Point-of-Use and Point-of-Entry)

Sometimes a chlorinator, faucet filter (point-of-use unit), dwelling filter (point-of-entry unit), or UV light disinfection unit is suggested to make an on-site polluted water supply safe for drinking without regard to the type, amount, or cause of pollution. This is hazardous. Instead, every effort should first be made to identify the pollutant and remove the source. This failing, every effort should be made to obtain water from a public water system. As a last resort, a household treatment unit or bottled water may have to be used. But the treatment units do not remove all microbiological, chemical, and physical pollutants. Careful selection of the proper treatment unit, which will resolve the particular pollution problem, in addition to cost, required maintenance and operation control, must be considered.

Household treatment unit processes include filtration, UV light radiation, chlorination, granular or powdered activated-carbon filtration, reverse osmosis, cartridge filters, cation exchange, anion exchange, distillation, pasteurization,[147] and activated-alumina filtration, as well as sand, porous stone, and ceramic filters. Each has limitations.

Ultraviolet light radiation and chlorination units are not considered satisfactory for the purification of surface-water supplies such as from ponds, lakes, and streams, which usually vary widely in physical, chemical, and microbiological quality, or for well or spring supplies, which may contain turbidity, color, iron, or organic matter. Pretreatment, usually including coagulation, flocculation, sedimentation, filtration, and disinfection or the equivalent, would be required to remove organic and inorganic contaminants that interfere with the effectiveness of the treatment. Chlorination and UV radiation treatment may be considered microbiologically acceptable only if the water supply is always clean, clear, and not subject to chemical or organic pollution and the units are operated as intended.* Certain controls are needed to ensure that the efficiency of the UV unit is not impaired by changes in light intensity, loss of power, rate of water flow, short circuiting, condition of the lamp, slime accumulation, turbidity, color, and temperature of the water.[148] Public Health Service 1974 standards state that acceptable UV units must have a flow rate of less than 0.2 gpm/effective inch of lamp, which must emit 2437 Å at an intensity of 4.85 UV watts/ft^2 at a distance of 2 inches, or an equivalent ratio of lamp intensity to flow, with a minimum retention time of 15 seconds at the maximum flow rate.[149] A flow control device, UV light-sensing device, alarm, and shutdown device are also needed.[150] Ultraviolet radiation units have application in the dairy, beverage, pharmaceutical, cosmetic, electronic, and food industries for the treatment of wash and cooling waters and for lowering the bacterial count in potable water used for soft drinks and bottled water. A chlorination unit requires inspection, solution replacement, and daily residual chlorine tests to ensure the unit operates as intended.

Most household filters contain activated carbon for the removal of organic substances. Taste and odor compounds are reduced, including chlorine, radon, and volatile halogenated organics such as trichloroethylene and carbon

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*Normal chlorination treatment and UV radiation treatment do not inactivate the *Giardia lamblia* and *Cryptosporidium* protozoan cysts.

tetrachloride.[151] Sediment is trapped in the filter, and organic compounds, such as trihalomethanes resulting from chlorination, are removed to some extent. The activated-carbon filter cartridge needs periodic replacement, as recommended by the manufacturer. Microorganisms may grow in the filter and be released, but no harmful effects have been reported.[152] Many volatile organic compounds and radon are also removed by boiling and aeration. A cartridge filter to remove particulates should precede the carbon filter if the raw water is turbid. It should be understood that the water to be filtered must be potable. Microbiological and inorganic contaminants in solution are not removed.

A reverse-osmosis filter can reduce the concentrations of fluoride, mercury, lead, nitrates, sodium, iron, sulfate, alkalinity, total dissolved solids, and similar substances that might be present in drinking water, but not radon (GAC is effective). Sediment and many organic compounds are also removed, but prefiltration through a filter that removes particulates is indicated if sediment is present to prevent premature membrane clogging, followed by an activated-carbon filter to remove taste and odor compounds and other organics.[153] Arsenic and uranium are also removed under certain operating conditions.[154] The unit should have an automatic shut-off valve. The filter membrane requires backwashing.*

An activated-alumina unit can reduce the fluorides, arsenic, barium, and nitrates if sulfates are not too high. Uranium is also reduced.[155] The unit requires periodic regeneration. The activated-alumina lead removal cartridge is effective in removing lead.[156]

Electric distillation units that boil and condense water are also available. These units remove most microorganisms and inorganic compounds, including lead, salt, and nitrates, but not volatile organic compounds like benzene and chloroform—their capacity is limited.

Special ion exchange cartridge filters can remove inorganic contaminants from drinking water, including fluoride, uranium, and arsenic.[157] Ion exchange units can be regenerated with sodium chloride.

Porous stone “candles” and unglazed porcelain Pasteur or Berkefield filters for microbiological control are available and can be attached to a faucet spigot. They may develop hairline cracks and become unreliable for the removal of pathogenic microorganisms. They should be scrubbed, cleaned, and sterilized in boiling water once a week. Portable pressure-type ceramic microfiltration units, with single or multiple candles, having a capacity to remove 0.2-μm particles (bacteria, protozoa, helminths, and fungi), but not all viruses or chemical contaminants, are also available.[158]

Environmental Protection Agency studies of home water treatment filter devices showed THM removals of 6 to 93 percent and total organic carbon removals of 2 to 41 percent, depending on the unit. In some cases, higher bacterial counts were found in the water that had passed through the filter.[159] A subsequent study showed similar results.[160] Another study of halogenated organic

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*Typically, about 75 percent of the tap water put into the reverse-osmosis system is wasted. (“FACTS for Consumers,” Federal Trade Commission, Washington, DC, August 1989, p. 2.)

removal showed reductions ranging from 76 percent for a faucet-mount unit to 99 percent for several line bypass units.[161] These filter units do not remove nitrates, fluorides, or chlorides; do not soften water; remove little dissolved lead, iron, manganese, and copper; and do not remove microorganisms. They should not be used on any water supply that does not otherwise meet drinking water standards. The ability of a unit to remove the particular deleterious contaminants in the raw water should be confirmed with the manufacturer and the health department before purchase.* In general, reverse osmosis and distillation are most effective for inorganic contaminant reduction and granular activated carbon for organic contaminant removal.

Household treatment units have a limited flow capacity, which can be compensated for in part by incorporating a storage tank in the water system. Provision must be made for replacement or washing and disinfection of the filter element on a planned basis.

The satisfactory operation of a large number of household point-of-entry units in an area requires an effective management system, including monitoring, maintenance, and timely replacement of units or components and, in some instances, pre–and post–water treatment such as preclarification and postdisinfection.[162]

Desalination

Desalination or desalting is the conversion of seawater or brackish water to fresh water for potable and industrial purposes. The conversion of treated wastewater to potable water using multiple desalination processes is also being utilized in water scarce areas of the world. This conversion uses a variety of technologies to separate the dissolved solids from a source water. Desalination technology is being used to remove contaminants from surface and underground waters, including inorganics, radionuclides, emerging contaminants (such as pharmaceuticals), and THM precursors.

Many countries have used desalination technology for decades having either exhausted all of their primary sources of freshwater or to supplement and diversify their portfolio of water supplies. Considered by many as a drought-proof and inexhaustible supply of *new* water, municipal planners in the United States are also turning to desalination treatment plants as a means to ensure water supply in times of extended drought or as a back-up supply during an emergency. California for example, has 16 desalination plants with a combined capacity exceeding 400 mgd, in either planning, design, piloting, or construction as of 2008.

About seven-tenths of our globe is covered by seawater. The world's oceans have a surface area of 139,500,000 mi^2 and a volume of 317,000,000 mi^3.[163] The oceans contain about 97 percent of the world's water; brackish inland sites

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*The National Sanitation Foundation, 3475 Plymouth Road, Ann Arbor, MI 48106, can provide a list of units certified for specific purposes. Also, The Water Quality Research Council, 4151 Naperville Road, Lisle, IL 60532.

and polar ice make up 2.5 percent, leaving less than 0.5 percent fresh water to be used and reused for municipal, industrial, agricultural, recreational, and energy-producing purposes.[164] In addition, more than half of the earth's surface is desert or semidesert. Under circumstances where adequate and satisfactory groundwater, surface water, or rainwater is not available and a high-quality water is required but where seawater or brackish water is available, desalination may provide an answer to the water problem. For seawater applications however, construction of intakes and the discharge of brine concentrate make siting new seawater plants a challenge. Prior to 2000, the high amounts of energy used in a desalination plant rendered plants feasible only where: 1) energy was plentiful and cheap; 2) where there were absolutely no other choices in water supply, or 3) the application was low volumes of high value product water such as for beverages, pharmaceuticals, or the electronics industry. Today however and with technology advances in both membrane materials and energy recovery, desalination costs are now affordable—even for high volumes of low-value water such as a municipal application.

Having begun in the arid Middle East 40 years ago with thermal (or distillation processes), desalting plants are now in use all over the world. Global Water Intelligence and the International Desalination Association reports 12,791 plants worldwide with capacity exceeding 11,000 mgd (over 42 million cubic meters per day) in operation as of 2006.[165]

Seawater has a total dissolved solids (TDS) concentration of about 35,000 mg/l. About 78 percent is sodium chloride, 11 percent magnesium chloride, 6 percent magnesium sulfate, 4 percent calcium sulfate, with the remainder primarily potassium sulfate, calcium carbonate, and magnesium bromide, in addition to suspended solids and microbiological organisms. The U.S. Geological Survey classifies water with less than 1,000 mg/l TDS as fresh, 1,000 to 3,000 mg/l as slightly saline, 3,000 to 10,000 mg/l as moderately saline, 10,000 to 35,000 mg/l as very saline, and more than 35,000 mg/l as brine. The U.S. Office of Technology Assessment defines potable water as generally having less than 500 ppm TDS (salt and/or dissolved solids), less brackish water as 500 to 3,000 ppm, moderately brackish water as 3,000 to 10,000 ppm, and highly brackish water as 10,000 to 35,000 ppm.[166] The source of brackish water may be groundwater or surface-water sources such as oceans, estuaries, saline rivers, and lakes. Its composition can be extremely variable, containing different concentrations of sodium, magnesium, sulfate, calcium, chloride, bicarbonate, fluoride, potassium, and nitrate. Iron, manganese, carbon dioxide, and hydrogen sulfide might also contribute to the variability of brackish water quality.

Desalting will remove dissolved salts and minerals such as chlorides, sulfates, and sodium, in addition to hardness. Nitrates, nitrites, phosphates, fluorides, ammonia, and heavy metals are also removed to some degree, depending on the process. Very hard brackish water will require prior softening to make reverse osmosis or electrodialysis very effective.[167] Desalination is not normally used to remove iron, manganese, fluorides, calcium, or magnesium.

Some known methods for desalting water are as follows[168]:

- *Membrane:* Reverse osmosis; electrodialysis and electrodialysis reversal; transport depletion; piezodialysis
- *Distillation or Thermal:* Multistage flash distillation; multieffect multistage distillation; vapor compression; vertical tube distillation; solar humidification
- *Crystallization:* Vacuum freezing–vapor compression; secondary refrigerant freezing; eutectic freezing; hydrate formation
- *Chemical:* Ion exchange

Distillation In distillation or thermal desalination, seawater is heated to the boiling point and then into steam, usually under pressure, at a starting temperature of 250°F (121°C). The steam is collected and condensed in a chamber by coming into contact with tubes (condenser–heat exchanger) containing cool seawater. The heated saline water is passed through a series of distillation chambers in which the pressure is incrementally reduced and the water boils (made to "flash"), again at reduced temperature, with the production of steam, which is collected as fresh water. The remaining, more concentrated, seawater (brine) flows to waste. In each step, the temperature of the incoming seawater is increased by the condenser–heat exchangers as it flows to the final heater. The wastewater (brine) and distilled water are also used to preheat the incoming seawater. This process is referred to as multistage flash distillation (MSF). There may be as many as 15 to 25 stages. A major problem is the formation of scale (calcium carbonate, calcium sulfate, and magnesium hydroxide) on the heat transfer surfaces of the pipe or vessel in which the seawater is permitted to boil. This occurs at a temperature of about 160°F (71°C), but scale can be greatly minimized by pretreating the seawater to remove either the calcium or the carbon dioxide. Distilled sea water normally has 5 to 50 mg/l salt. Most volatile substances are removed.

Vertical-tube distillation, multieffect multistage distillation, vapor compression distillation, and solar distillation are distillation variations. Solar humidification (distillation) depends on water evaporation at a rate determined by the temperature of the water and the prevailing humidity. The unit is covered with a peaked glass or plastic roof from which the condensate is collected. Distilled water is tasteless and low in pH if not aerated and adjusted before distribution.

Reverse Osmosis Normally, if salt water and fresh water are separated by a semipermeable membrane, the fresh water diffuses through to the salt water as if under pressure, actually osmotic pressure. The process is known as osmosis. In reverse osmosis, hydraulic pressures of 200 to 500 psi for brackish water and 800 to 1,200 psi for seawater[169] are applied to the concentrated salt water on one side of a special flat or cylindrical supported membrane, a spiral wound, or hollow-fiber unit. The life of the membrane decreases with increasing pressure. In the process, fresh water is separated out from the salt water into a porous or hollow channel from which the fresh water is collected. The concentration of

TDS in the salt water flowing through the unit must be kept below the point at which calcium sulfate precipitation takes place. Some of the dissolved solids, 5 to 10 percent, will pass through the membrane, including total hardness, sulfates, chlorides, ammonium, chemical oxygen demand (COD) materials, color, bacteria, and viruses. Chlorinated methanes and ethanes, which are common solvents, are not removed by reverse osmosis; however, air stripping is effective.[170] An increase in the TDS will result in a small increase of solids in the fresh water.

In reverse osmosis, the salt water to be treated must be relatively clear and free of excessive hardness, iron, manganese, and organic matter to prevent fouling of the system membranes. The maximum water temperature must be between 86° and 122°F (30° and 50°C), depending on membrane type.[171] Since the RO elements are designed to remove only the dissolved material in the source water, all suspended particles must be removed before entering the RO membranes, or the elements will become fouled prematurely. The pretreatment of the source water is a critical component of a well-designed plant and may consist of:

1. Softening to remove hardness;
2. Coagulation and filtration (sand, anthracite, multimedia; cartridge, or diatomaceous earth) to remove turbidity, suspended matter, iron, and manganese;
3. Low pressure micro filtration (MF) or ultra filtration (UF) membranes for turbidity and suspended particle removal; and
4. Filtration through activated-carbon columns to remove dissolved organic chemicals.

If the pretreatment design uses conventional process (coagulation/sedimentation/sand filtration), a 1 micron cartridge or bag filter is installed between the sand filter and the RO elements. This disposable filter is an insurance step to prevent an accidental loading of unwanted foulant material onto the RO elements. Acid is used if necessary to lower the pH and prevent calcium carbonate and magnesium hydroxide scale. Citric acid is used to clean membranes of inorganic and chlorine bleach for organics removal. Special cleaners may be needed to remove silicates, sulfates, hydroxides, and sulfides. Chlorine might also be used to control biological growths on the membranes,[172] but prior filtration of water through GAC is necessary to protect membranes not resistant to chlorine and prevent the formation of trihalomethanes (bromoform). Salt, dissolved solids, some microorganisms, organic and colloidal materials, and other contaminants, including radiologic, are removed. Reverse-osmosis treated water usually requires posttreatment for pH adjustment, degasification (H_2S and CO_2), corrosion adjustment, and disinfection, possibly further demineralization by ion exchange, and UV radiation disinfection for certain industrial waters. Other membrane processes include nanofiltration, ultrafiltration, and microfiltration.

Electrodialysis In electrodialysis, the dissolved solids in the brackish water (less than 10,000 mg/l TDS) are removed by passage through a cell in which a direct electric current is imposed. Dissolved solids in the water contain positively charged ions (cations) and negatively charged ion (anions). The cations migrate to and pass through a special membrane allowing passage of the positive ions. Another special membrane allows the negative ions to pass through. The concentration of dissolved solids determines the amount of current needed. The process removes salt, other inorganic materials, and certain low-molecular-weight organics.[173] Operating pressures vary from 70 to 90 psi. The partially desalted–demineralized water is collected and the wastewater is discharged to waste. Maximum water operating temperature is 113°F (45°C).[174]

The plant size is determined in part by the desired amount of salt removal. However, a change in the TDS in the brackish water will result in an equal change in the treated water.[175] As in reverse osmosis, pretreatment of the brackish water is necessary to prevent fouling of the membranes and scale formation. Scaling or fouling of membranes is reported to be prevented in most units by reversing the electric current at 15- to 30-minute intervals.[176] The cost of electricity limits the use of electrodialysis.

Transport depletion is a variation of the electrodialysis process. Piezodialysis is in the research stage; it uses a new membrane desalting process.

Ion Exchange In the deionization process, salts are removed from brackish water (2,000 to 3,000 mg/l TDS). Raw water passes through beds of special synthetic resins that have the capacity to exchange ions held in the resins with those in the raw water.

In the two-step process, at the first bed (acidic resin) sodium ions and other cations in the water are exchanged for cations (cation exchange) in the resin bed. Hydrogen ions are released and, together with the chloride ions in the raw water, pass through to the second resin bed as a weak hydrochloric acid solution. In the second resin bed, the chloride ions and other anions are taken up (anion exchange) from the water, are exchanged for hydroxide ions in the resin bed that are released, combine with the hydrogen ions to form water, and pass through with the treated water. The ion exchange beds may be in a series or in the same shell.

When the resins lose their exchange capacity and become saturated, the treatment of water is interrupted and the beds are regenerated, with acids or bases. The resins may become coated or fouled if the raw water contains excessive turbidity, microorganisms, sediment, color, or organic matter, including dissolved organics, hardness, iron, or manganese. In such cases, pretreatment to remove the offending contaminant is necessary. Chlorine in water would attack the cation resin and must also be removed prior to deionization.

Waste Disposal The design of a desalting plant must make provision for the disposal of waste sludge from pretreatment and also of the concentrated salts and minerals in a solution removed in the desalting process. The amount or volume of waste is dependent on the concentration of salts and minerals in the raw water and the amount of water desalted. The percent disposed as waste concentrate from a reverse osmosis unit treating brackish water may be 20 to 50 percent, from a seawater unit 60 to 80 percent, from an electrodialysis unit 10 to 20 percent, and from a distillation unit 5 to 75 percent.[177]

TABLE 1.17 Country Inventory of Global Desalination Treatment Plants

Country	No. of Plants	Treatment Technology		User Category		Source Water		
		Membrane	Thermal	Municipal	Industrial[a]	Seawater	Brackish	Other[b]
Algeria	147	75%	25%	68%	32%	73%	19%	8%
Australia	181	74%	26	15%	85%	18%	46%	36%
Bahrain	140	26%	74%	77%	23%	91%	9%	—
China	189	84	16	48	52	45	13	42
India	193	57	43	9	91	68	18	14
Israel	50	97	3	98	2	87	11	3
Japan	1457	95	5	19	81	17	16	67
Kuwait	84	16	84	85	15	84	2	14
Libya	295	18	82	74	26	87	13	—
Oman	133	39	61	92	8	96	3	1
Qatar	87	2	98	96	4	99	1	—
Saudi Arabia	2086	41	59	84	16	79	20	1
Spain	760	95	5	83	17	72	21	7
UAE	351	20	80	95	5	98	2	—
USA	2174	95	5	63	37	12	49	39
Total[c]	8327							

[a] Industrial includes other categories such as power, irrigation, military, tourism

[b] Other source waters include: river water, wastewater, pure water

[c] These 15 countries contain 8327 of the total number of 12,791 global plants

Source: IDA Desalination Yearbook 2007-2008, T. Pankratz and E. Yell; Media Analytics, Ltd., Oxford, UK 2008.

The waste from mildly brackish water (1000 to 3000 mg/l TDS) will contain from 5,000 to 10,000 mg/l (TDS). The waste from a seawater desalting plant can contain as much as 70,000 mg/l (TDS).[178]

The waste disposal method will usually be determined by the location of the plant and the site geography. Methods that would be considered include disposal to the ocean, inland saline lakes and rivers, existing sewer outfalls, injection wells or sink holes where suitable rock formations exist, solar evaporation ponds, lined or tight-bottom holding ponds, or artificially created lakes. In all cases, prior approval of federal (EPA) and state regulatory (water pollution and water supply) agencies having jurisdiction must be obtained. Surface and underground sources of drinking water and irrigation water must not be endangered.

Table 1.17 presents an inventory of the top 15 countries incorporating desalination technology as of 2006. In addition to the number of installed plants in each country, the table presents the technology used, the application categories, and the source of the water supply.

Costs The Office of Water Research and Technology reported that the cost of desalted water from global desal plants varies from upward from 85 cents per 1,000 gallons, except where fuel is available at very low cost.[179]. In 2007, the costs in the United States for seawater ranged from \$2.00 to \$6.00 per 1000 gallons depending on the size of the plant. Commissioned in late 2007 for example, the total cost of water from the Tampa Bay Water desalination plant cost approximately \$3.18 per 1000 gallons. This is the largest operating plant in the United States at 28 mgd, although two 50 mgd plants are scheduled to begin construction in Carlsbad and Huntington Beach California in 2009. [180] Costs in 1985 (capital and operating costs) were estimated to be \$2 to \$2.50 per 1,000 gallons for brackish water, reverse osmosis, and electrodialysis treatment, with conventional treatment at approximately \$0.40 to \$2 per 1,000 gallon.[181]

An analysis was made by Miller[182] of 15 municipalities in the western United States demineralizing brackish water by reverse osmosis, electrodialysis, or ion exchange and combinations thereof. Flows varied from 0.13 to 7.18 mgd and TDS from 941 to 3,236 mg/l. The demineralization cost varied from \$0.37 to \$1.56 per 1,000 gal. Reverse osmosis was found to be the least costly process by most of the communities. Reverse osmosis plant construction and operating costs for seawater desalting were reported to be usually less than for distillation.[183] This may not be the case, however, where large volumes of seawater are to be distilled and where a convenient source of heat energy is available,[184] such as from a power plant or incinerator or where fuel costs are low. In another report, the energy break-even point of the reverse osmosis and electrodialysis treatment of brackish water and wastewater was approximately 1,200 mg/l. Electrodialysis was more energy efficient below 1,200 mg/l and reverse osmosis above that level.[185]

Construction and operating cost comparisons must be made with care. They are greatly influenced by location; material, labor, and energy costs; size; TDS concentration; and amount of pollutants such as suspended and other dissolved solids in the water to be desalted. Waste disposal and water distribution are additional factors usually considered separately.

General The use of desalted water usually implies a dual water distribution and plumbing system, one carrying the potable desalted water and the other carrying nonpotable brackish water or seawater. Obviously, special precaution must be taken to prevent interconnections between these two water systems. The brackish water or seawater may be used for firefighting, street flushing, and possibly toilet flushing.

The finished desalted water requires pH adjustment for corrosion control (lime, sodium hydroxide) and disinfection prior to distribution. It must contain not more than 500 mg/l total dissolved solids to meet drinking water standards. Up to 1,000 mg/l dissolved solids might be acceptable in certain circumstances. Other standards would apply if the desalted water is used for industrial purposes. The EPA considers a groundwater containing less than 10,000 mg/l TDS as a potential source of drinking water.[186]

Indirect benefits of desalting brackish water may include the purchase of less bottled water, use of less soap and detergents, no need for home water softeners and water-conditioning agents, and fewer plumbing and fixture repairs and replacements due to corrosion and scale buildup.[187]

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