Subcontractor Report

June 2003 • NREL/SR-500-30383

Renewable Energy in Water and Wastewater Treatment Applications

Period of Performance:
April 1, 2001 – September 1, 2001

N. Argaw

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Contract No. DE-AC36-99-GO10337

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NREL Technical Monitor: L. Flowers

Prepared under Subcontract No. AAM-1-31224-01

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Forward

The availability of clean drinking water is a development issue faced by billions of people in the developing and near-developed world. Development organizations continually site the lack of access to clean water and sanitation as the leading cause of death amongst children in rural areas. The scale of this problem is immense, as are its solutions. The global nature of this issue opens the door for the application of communal solutions, as was demonstrated by the discussions surrounding the Johannesburg global climate meeting where water issues were a key concern that all nations could come together to support.

Like energy, the need for clean water is increasing rapidly as supplies of traditional resources continue to diminish due to overuse, waste, and pollution. Unlike energy, the ability to harness local resources to produce water is not possible. However, we do have the capability to use local energy resources to gain access to water supplies that would otherwise be unavailable and then ensure that this water is safe for human consumption. Most water is located underground in deep aquifers, in surface lakes, rivers, and streams or in the ocean. Technologies exist to make use of all of these water sources but in many cases, the absence of available, inexpensive energy makes their use expensive, time consuming, and potentially dangerous. The proper application of any number of energy options available today can make gaining access to this water a reality in many areas not previously considered.

This report, one of three written by the author, provides insight into providing water to people in rural areas. By considering all aspects of water systems from assessing availability, accessibility, treatment, supply systems, and post use treatment, this document provides insight into all aspects of the water system. The document also discusses a variety of energy sources available to rural and remote areas to provide power for any proposed water systems. The report is unique as it provides a very evenhanded approach to the selection of different technologies and power choices.

The purpose of this document is to provide insight into the different options that are available and methods to understand which technology may be the best for specific needs, conditions, and locations. We also hope to dispel some of the misconceptions about appropriate or inappropriate technologies through the publication of this document. Because the access to clean water is such a large and encompassing issue, all solutions have their place. The difficulty is determining which technologies are most appropriate for each user's specific need.

This book is one in a series of guidebooks that NREL produced, with the support of the U.S. Department of Energy, to couple commercial renewable energy systems with rural applications, including other water issues, rural schools, health posts, and micro-enterprise. Other water related publications in this series describe the technical aspects of water pumping technology and provide insight to issues of water treatment, specifically purification, desalination, and wastewater treatment.

E. Ian Baring-Gould
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Chapter 1: Introduction

Background

Absolutely pure water is not found in nature. Water evaporates into the atmosphere, condenses, and when it falls back to the ground, the water contains dissolved gases including oxygen, carbon dioxide, bacteria, and dust absorbed from the air. Once the water hits the ground, it picks up many more organic and non-organic chemicals, microorganisms, and organisms as it make its way into streams and rivers. Some of the rainfall percolates into the soil, loosening suspended silt and bacteria. There is also the danger of contamination by radioactive isotopes in the groundwater. Contaminants from the ground's surface include municipal, industrial, and agricultural wastes. These wastes wash into rivers and also infiltrate the groundwater. Depending on the intended use, all of these contaminants need some kind of treatment.

Generally, wastewater requires a certain level of treatment before it can come into contact with the surface or with groundwater. Similarly, domestic water should be clean and safe to drink. Depending on the source, domestic water requires some kind of treatment.

Renewable energy sources have been used and will continue to be used, either directly or indirectly, in water and wastewater treatment. Solar energy—typically stabilization ponds and solar detoxification—is often used for wastewater treatment and is still used in many countries.

Solar energy is still the simplest technology for desalination of salty waters, and for water disinfection. Solar still is the simplest desalination technology. It can be converted into electricity, which can be used to power pumps, ultraviolet (UV) systems, photocatalysis, reverse osmosis (RO), and conventional surface-water treatment systems.

Similarly, wind energy has been used since 1200 BC by the Persians. In the early 1900s, the American Farm windmills supplied water for both the railroads and for domestic uses. Windmills continue to be very popular for pumping water. Today, there are more than one million windmills in the United States, Argentina, and Australia alone. Like solar photovoltaic (PV) systems, wind turbines convert wind energy directly into electricity, and the electricity produced can be used to power water treatment systems. However, wind machines are normally not used for wastewater treatment since most wastewater treatment systems have very large power requirements or require direct sunlight (e.g., stabilization ponds).

Today, however, renewable energy sources, unlike conventional power sources (petroleum-based gensets and power from the grid), are mostly used for small to medium applications because of their high initial investment costs. The power needed to treat a rural water supply is relatively small and for this reason renewable energy power sources are widely used in many developing countries.

Purpose of This Book

This guidebook is to help readers understand where and how renewable energy technologies can be used for water and wastewater treatment applications. It is specifically designed for rural and small urban center water supply and wastewater treatment applications. This guidebook also provides basic information for selecting water resources and for various kinds of commercially available water supply and wastewater treatment technologies and power sources currently in the market.

Chapter 2 discusses water resources, raw water quality, and water storage. Chapters 3 and 4 present the available energy resources for water-supply applications and the kinds of rural water-supply technologies. Chapters 5 and 6 provide basic information about water purification technologies and wastewater sources and treatment. Chapter 7 discusses appropriate technology assessment, and Chapter 8 presents the bibliography.

Chapter 2: Water Resources and Water Quality

Water is a fundamental part of life, and for years everyone took it for granted. Recently, governments and concerned individuals worried that water resources were finite and could be lost to contamination or sudden loss, or from the pressure of large-farm irrigation that would create physical and chemical stresses. The decline of the underground water table (e.g., in Phoenix, Arizona) and an increase in the salinity of the water through excessive use of water for irrigation (e.g., the Colorado River) are prime causes for concern about water resources and their quality.

Water Resources

Apart from its day-to-day use for drinking, irrigation, and marine life, water is used for many applications. It is used as a solvent (water dissolves more substances in greater quantities than any other liquid), for heating spaces (except for liquid ammonia, water has the highest heat-transfer capacity, and is better suited for heating buildings), and for its ability to conduct electricity through dissociation, when acid is added (e.g., in automobile batteries). Therefore, it is necessary to understand the existence of water. For example, the presence of underground water depends not only on the creation of the storage facilities (between rocks, clays, and permeable soils) but also on nature's ability to keep them supplied. We all know that there can be an abundance of water in one area or scarcity in other. To understand why water is present, we need to know the reasons for the uneven distribution of precipitation over the earth's surface and the processes involved in the movement of water from place to place. In principle, the total volume of water on this planet is finite and constant, but the uneven distribution of water on the earth's surface is due to hydrological cycle and weather patterns. The hydrological cycle of water can be easily visualized from Figure 2.1.

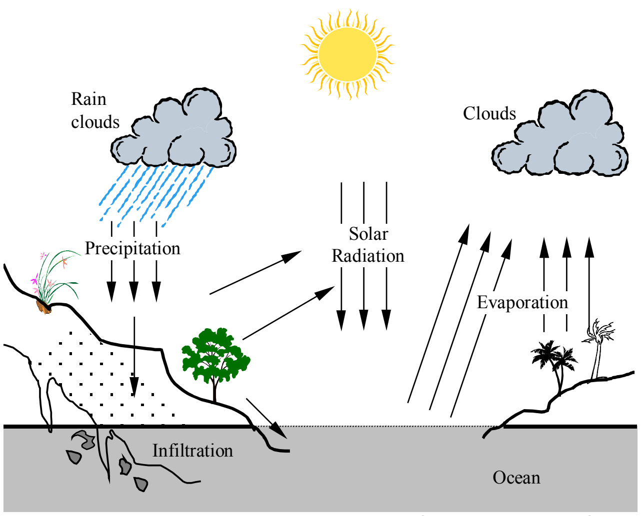


Figure 2.1. The hydrological cycle of water: water from the sea evaporates to form clouds; falls back to earth as precipitation; and via streams, rivers, and infiltration, returns to the sea.

In principle, it is solar energy that causes the uneven distribution of water on the earth's surface. The water itself serves as a thermal energy storage medium, which determines the three parameters of climate: air temperature, air pressure, and precipitation. When solar radiation strikes the earth's surface, the earth is heated. At the Equator, there is a net heat gain, while at the poles, there is a net heat loss. Through the movement of the oceans and the atmosphere, the surplus heat moves toward the poles. The cool air is heated when it reaches the earth's surface and rises back into the atmosphere, while the warm rising air that contains water through evaporation eventually cools and falls back to earth as rain. Water from the sea evaporates to form clouds, returns to the earth as precipitation, and via streams, rivers, and infiltration, returns to the sea. This process is called the hydrologic cycle. This cycle creates certain weather patterns so that one location is dry while another location is wet. Therefore, the sources of water vary from one locality to another. However, the availability of groundwater depends not only on the hydrologic cycle and weather pattern. It also depends upon the formation of aquifer systems. The formation of aquifers can be from weathering, erosion, glacial deposits, sedimentary rocks, alluvial aquifers, and/or igneous and metamorphic rock aquifers.

There are two main water sources: surface water and groundwater. Surface water sources are rivers, streams, man-made ponds or reservoirs, lakes, and seas. Streams are generally seasonal; depending on the size and tributaries, river-water sources can be seasonal or year round. Seasonal water sources require man-made dams or reservoirs for water supply and irrigation purposes. However, water resources from year-round rivers or lakes do not require such storage. Generally, surface waters require treatment for domestic water supply, and this will be discussed in the following chapters.

Groundwater resources are formed when the surface is over-saturated and the excess water filters down. The depth of the soil water zone varies from about 1 meter (m) to 9 m (3 feet (ft) to 30 ft). Water is also lost by transpiration and evaporation. Soil undergoes wide variations in moisture content—from complete saturation to a total lack of moisture. Water is held in the soil by molecular or capillary attraction, acting against the force of gravity. Molecular attraction holds water in a thin film on the surface of each soil particle. Capillary attraction holds water in the smallest spaces between soil particles. Water begins to percolate downward under the force of gravity when the water-holding capacity of the capillary forces is exceeded. The region immediately below the soil water zone is called the intermediate zone. Most water in this zone will move downward, has no in-situ use, and cannot be recovered. There is a capillary fringe at the bottom of the intermediate zone where groundwater is drawn upward by capillary forces. Depending on the kind of aquifer, water may migrate upward more than 3 m (Driscoll 1986). Well-sorted, fine sediments are most effective at holding water and are often completely saturated within the capillary fringe zone; coarse sediments are not as effective in holding water.

The groundwater table lies at the very bottom of the capillary zone. Generally, subsurface water used for domestic purposes and irrigation is pumped from below the groundwater table. However, groundwater can also be springs or artesian wells, where water is forced from the aquifer by compaction caused by the weight of overlying sediments or a well that derives its water from a confined aquifer in which the water level is above the ground surface. In such cases, groundwater is capped at the surface (at the eye of the spring or artesian well).

Groundwater found in shallow wells can generally be extracted using hand pumps or with a simple pulley and bucket. Such wells can be dug by hand or bored using earth augers. There are three main types of earth augers: large-diameter bucket augers, solid-stem augers, and hollow-stem augers. Large-diameter bucket augers are most commonly used to drill up to about 45 m (150-ft) deep and up to 1.2 m (48–inch [in]) diameter wells. Solid-stem augers can drill up to 35 m (120 ft) deep and up to 600 millimeters (mm) (24 in) in diameter. The most common depth for hollow-stem augers in stable formations are 35 m (120 ft) for a 150 mm (6 in) diameter hollow-stem auger and about 12 m deep for a 300 mm (12-in) diameter hollow-stem auger (Driscoll 1986). Generally, deep wells are drilled using drilling machines. There are several types of drilling methods, depending on the geologic formation and the depth and diameter of the well.

Particular drilling methods become dominant in certain areas because they are most effective in penetrating the local aquifers and thus offer cost advantages. Some of the most common drilling machines are cable tool drills, direct- and reverse-circulation rotary drills, and air drills. Rotary drilling machines are mostly used to reach greater depths and to increase drilling speeds. Normally drilling fluids (air, clean water, and mixtures of special-purpose materials) are essential for efficient rotary drilling. However, direct rotary drilling is very expensive because drill bits are costly and drilling rigs require a high level of maintenance. Reverse circulation drilling is generally most successful in soft sedimentary rocks and unconsolidated sand and gravel where the static water level is 3 m (10 ft) or more below ground level. This drilling method is the least expensive for drilling large-diameter holes in unconsolidated formations.

Springs are commonly found at the foot of mountains. Mountains are also sources of streams, and many streams flow into rivers. Some rivers flow into larger rivers, such as the Amazon or the Nile. When streams and rivers flow over a flat area, the surrounding area will generally have good underground water because water soaks into the aquifer. Such areas are generally good for shallow wells. Although surface and rainwater infiltration are the main sources for enriching underground water sources, water also flows underground through fractured rocks and aquifers, depending on the hydrological formations of the ground. The best aquifers are coarse sand and gravel, limestone openings, sandstone, or fractured rocks, and aquifers, such as clay, silt, and solid metamorphic rock like marble have very minimal water penetration. An aquifer on the surface of the ground, having a reasonable depth and followed by a layer of impermeable materials (e.g., solid rock, silt, or clay), is considered to be a good catchment area for underground water. Therefore, a detailed geological survey should be made before drilling. More than 40% of the wells drilled in developing countries for domestic water supply are abandoned due to lack of sufficient water.

Raw Water Quality

The source of the water determines its characteristics. Generally, surface water is exposed to contamination due to human, animal, and industrial activities upstream. Surface water can be contaminated with both pathogenic and non-pathogenic organisms and suspended solid particles from precipitation or runoffs. Treatment methods for these contaminants are discussed in Chapters 4 and 5. On the other hand, groundwater is usually clear and odorless. Groundwater does not usually contain suspended solid particles or bacteria or organic matter, but does usually contain dissolved mineral ions (minerals are generally dissolved in water and the term *total dissolved solids* (TDS) refers to them). The type and concentration of these dissolved minerals can affect how the groundwater can be used. If certain minerals are present in excessive amounts, certain types of treatment may be necessary to change or remove the dissolved mineral before using the groundwater for its intended purpose. However, studies show that moderate TDS levels have some health benefits.

Although groundwater may not have bacteria, there is a risk of contamination, especially for shallow wells, from human and animal activities in the area. Contaminants can seep into the ground from the top of the borehole. Therefore, the area surrounding the borehole should have proper drainage to keep it dry, and the borehole should be properly capped.

The water quality level varies, depending on the intended purposes. Water used for irrigation can be very low quality, as long as it is not salty, which might burn the soil and crops. On the other hand, drinking water should fulfill the water quality standard guidelines set by national governments and the World Health Organization (WHO). Sources of contaminants are characterized as physical, chemical, bacteriological, and radiological. The WHO has guidelines for five categories of contaminants for drinking water:

1. Microbiological and biological standards (microorganisms and other organisms)
2. Inorganic constituents that pose health risks (arsenic, cadmium, nitrate, lead, and sodium)
3. Organic constituents (benzene, phenols, dichlorodiphenyltrichloroethane (DDT), and others)
4. Aesthetic guidelines (odor, taste, hardness, and color)
5. Radioactivity guidelines (mostly for groundwater).

Water Storage

Depending on the intended purposes and the kind of water resources, there might be a need to have raw water storage. Raw water storage is necessary if the water resource is not available year round. Although the demand for irrigation water is seasonal, it still requires large amounts of water, and dams or ponds (depending on the size of irrigation field) are mainly used for storage. Similarly, cities require large amounts of water and in most cases dams are used for storage. For rural water supply, however, dams (or any surface water source in general) are not recommended because surface water usually requires expensive treatment. If there is a groundwater source, several wells can be drilled, depending on the water demand. In some cases, runoff can be guided to flow into the groundwater catchment field for quick borehole recovery or for higher discharge. Such methods are also used to raise the groundwater table.

Generally, domestic water requires clean storage to improve water distribution management and to prolong the life of the pump. Water tanks can help improve water distribution networks and can even supply water while major or minor maintenance is being performed on pumping systems and distribution pipes. A critical factor for the life of a pump is how often the pump runs to fulfill the water demand. The size of the storage tank determines how often the pump is operating to meet the water demand.

Figure 2.2. A water storage system for cattle watering using a PV pumping system.

For watering cattle, the storage system can be designed in such a way that the cattle can drink directly from the storage. Usually, round steel or concrete water tanks, with a height not more than 1 m is used (see Figure 2.2). On the other hand, clean water storage for a domestic water supply can be designed based on the geographical location, topography of the area, and the water demand. The storage can be made of steel, polyvinyl chloride (PVC), fiberglass, concrete, or steel based on the conditions mentioned. In most cases, steel, fiberglass, and PVC tanks are used for renewable-energy-based (PV or wind) water supply systems. However, the size of the water tanks for renewable-energy-based systems should be large enough to fulfill the water demand for the worst-case situations (e.g. in case of continuous cloudy days). Water tanks for hybrid power

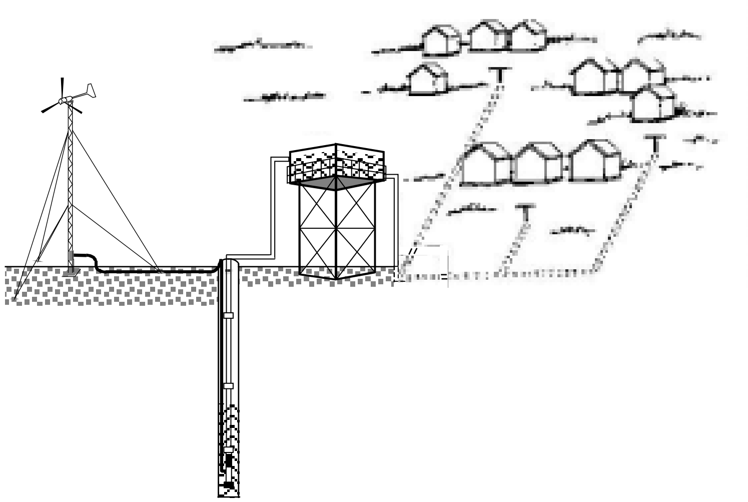


Figure 2.3. Schematic diagram of a typical village water supply storage tank and distribution network, powered by an electrical wind turbine.

systems (PV, wind, or backup genset) may not require oversized water tanks because backup power should be available either from the PV, wind, or backup genset system. Generally, elevated water tanks are used for PV- and wind-powered water supplies in rural areas to easily distribute the water to the communities using gravity. Such systems have simple distribution networks where the villagers get water from central distribution points. Figure 2.3 shows a typical rural water supply storage tank and distribution system installations. A water distribution system is not usually required for cattle watering. However, for a large cattle population, two or more cattle troughs (like the one shown in Figure 2.2) might be necessary. In such cases, water is distributed to each storage tank through a loop system, where all the tanks are interconnected.

Chapter 3: Energy Sources for Water-Supply Technologies

There are several power source options for rural water supply applications, including diesel/gasoline/kerosene pumps, grid-connected electric pumps, wind pumps, solar pumps, bio-fuel pumps, animal-drawn pumps, and hand pumps. Animal-drawn pumps and hand pumps are the cheapest and simplest form of pumps that can be used for pumping water from shallow wells. Such types of pumps are mostly used by low-income communities or by individual households in rural areas of many developing countries. Animal-drawn pumps are most operated by donkeys or oxen. Animal-drawn pumps for community use require a strong organization that can look after the draft animals as well as perform maintenance follow-up, which makes the system unsustainable. However, they can be good for individual use for small irrigation and water supply. On the other hand, hand pumps do not require a strong organization as long as the system is maintained regularly. Hand pumps require human labor to pump the water and in most cases are difficult to pump at higher elevations, especially for women and children, who are the main users. On the other hand, fossil-fuel-operated pumps, grid-connected electric pumps, wind pumps, and solar pumps do not require animal or human labor, but they are more expensive for low-income communities. Basic operating principles and the advantages and disadvantages of these pumping options will be discussed in the following sections.

The greatest problem in many developing countries is not in choosing the power source. There are several power source options available on the market to pump water. The problem is issues associated with policy decisions, which ultimately influence the selection of the pumping system. Some of these issues are related to government subsidies and favoring certain technologies; equipment standardization; dependence on imported equipment, fuel, and spare parts; proper design; and the installation and maintenance infrastructure of the country. Government subsidies for certain water-pumping technologies, mainly diesel and gasoline engines, reduce the competitiveness of alternative pumping options. Similarly, although equipment standardization has lots of benefits, it can block other alternative technologies and equipment features, especially for new emerging technologies, such as solar pumps. On the other hand, standardized equipment with a well-organized installation and maintenance infrastructure reduces unnecessary spending on spare-parts, reduces equipment breakdown and the need for qualified manpower for every type of product and pumping technology. Many engines are not optimally designed for rural villages; and they are not operating at full capacity, which contributes to increased maintenance requirements and system inefficiencies.

Diesel, Gasoline, and Kerosene Pumps

Diesel, gasoline, and kerosene engines are internal combustion engines with instant start-up capabilities, and a high power-weight ratio. These capabilities make them attractive to power small isolated machines such as water pumps, cars, and boats. These internal combustion engines are divided into compression ignition engines and sparked ignition engines. The compression ignition engines are fueled by diesel fuel, and sparked ignition engines are fueled by gasoline (petrol), kerosene, or liquefied petroleum gas (LPG).

Generally, internal combustion engines will have premature wear if they run continuously at a rated power. On the other hand, the optimum efficiency of most engines is achieved at around 70% to 80% of the rated power. Optimum efficiency is the point at which fuel consumption is the smallest. Therefore, derating engines around 70% to 80% is recommended. Further derating is also necessary at higher ambient temperatures and altitudes. A derating of 1% for each 5^oC temperature is necessary above 16°C, and 10% derating is necessary for every kilometer (km) above sea level. For example, for a 3-kilowatt (kW) load requirement at 2,000 m above sea level and 25^oC ambient temperature, the engine capacity should be from 4.8–5.5 kW.

Smaller internal combustion engines are normally started using a hand crank or a pull-cord starter; larger engines require an auxiliary electrical system and a battery with an electric starter. Generally, one-third of the heat produced in an internal combustion engine is dissipated through the walls of the engine cylinder, and air- or water-cooling is used for medium- to large-sized engines. Water-cooling controls the heat better and operates more quietly than air-cooling. However, corrosion is a problem unless a special anti-corrosion chemical is used. Another problem is engine damage if the cooling water runs out.

The cost of internal combustion engines depends mainly on the size and speed because a higher power-weight ratio is normally achieved by running an engine at high speed. When the engine runs at a higher speed, more air and fuel are burned, and more energy will be produced. Therefore, for the same rated power, smaller-sized, higher speed engines are cheaper than the heavy, lower-speed engines. However, higher-speed engines wear faster, so there should be a trade-off between the heavy, lower-speed, -expensive engines and the lightweight, higher-speed engines.

Transmitting the power from the engine to a pump depends on the type of engine and pump design. Power transmission can be directly coupled to the pump, gearbox transmission, or belt drives. Generally, transmission losses are negligible for direct couplings and high for gearbox drives.

Diesel Engines

Diesel engines are another form of combustion ignition. These engines ignite their fuel when compressed air is mixed with a pressurized fuel sprayed into the cylinder at the appropriate time and temperature for ignition. Diesel engines need to be heavier and more robust to allow for the pressure needed to cause compression ignition. The high compression ratio allows a diesel engine to draw more air per stroke in relation to the combustion space, while the fuel injection allows the air-fuel mixture to run more smoothly for ignition unlike spark ignition engines. The other advantage of diesel engines is the fuel itself. Diesel fuel is 18% richer in energy than gasoline per liter due to the fact that diesel fuel has higher density. Diesel engines can operate more hours per day compared to gasoline or kerosene engines. They have a longer operational life compared to spark ignition engines, and are generally heavier and more robust. They are generally more efficient (between 30%–40%) than spark ignition engines (25%–30%). However, small diesel engines tend be less efficient (as low as 15%). Several factors contribute to this lower efficiency, mainly the size, type, design quality, and age of the engine. The efficiency can be as low as 10% and as good as 35% depending on these factors.

Figure 3.1. Diesel generator at a rural Panamanian hospital.

Diesel engines are categorized as either high speed or low speed. Low-speed engines range from 450–1,200 revolutions per minute (rpm) and tend to be heavier and more expensive than high-speed diesel engines. Low-speed diesel engines have longer operational lives. On the other hand, high-speed engines operate between 1,200 and –2,500 rpm and, as stated, wear out faster and have shorter operational lives. The weight of high-speed engines per rated power is lower than the low-speed engines by almost half. High-speed engines do not typically operate more than 10 hours a day, while the low-speed engines can operate up to 24 hours a day.

Gasoline/Kerosene Engines

Spark ignition engines operate by mixing the vaporized fuel (gasoline, kerosene, or LPG) with air, compressing the mixture, and igniting it at the right moment with an electrical spark in the engine cylinder. A spark plug is used to create the electrical discharge in the cylinder for ignition. Spark ignition engines are lighter and more compact than diesel engines. They are generally cheaper than diesels. Such engines cannot be designed for a high compression ratio like a diesel engine because the fuel-air mixture would ignite prematurely and cause knocking. The caloric values of such fuels are also quite low compared to diesel fuel.

Spark ignition engines are usually designed for small applications (up to the 3-kW range) and are the best option for small, lightweight, and portable applications. They are simple to maintain and affordable for irrigation or for lighting a few households. These types of engines are ideal for low-head and high-discharge (mainly floating) pumps. However, these types of engines have a shorter operational life compared to diesels. Gasoline engines have a shorter daily operational life (approximately 4 hours) than kerosene engines, which can operate up to 6 hours a day. Gasoline engines are most commonly used for cars and light trucks.

Because kerosene does not vaporize adequately in a cold engine, most kerosene engines need to be started using gasoline until the engine warms up and need to be switched back to gasoline before the engine stops to make ready for the next startup. Most kerosene engines have a separate fuel compartment to store gasoline and a switch to alternate between the two compartments. Using both fuels in a kerosene engine is inconvenient for users (especially farmers) to buy and store. Kerosene engines require two different storage tanks to store these fuels. However, kerosene has approximately 10% more energy per liter than gasoline, and is less taxed in many countries. It is also easy to store since it is less dangerous than gasoline.

Grid-Connected Electric Pumps

Grid-connected pumps use electricity from the grid to run the electric motor. In developing countries, the grid power source is mainly from hydropower, coal, and diesel generator plants. Localized grids, such as a mini-hydropower grid or diesel generators, are very popular in developing countries to provide power for isolated and remote towns, where electric motors are used to pump water for the town's water supply. The electric motor generally requires a three-phase power supply from a nearby grid power line. Depending on the nearby utility grid power, a step-down transformer might be required to deliver the required voltage and amperage.

Grid-connected pumps are simple to install with low service requirements (especially for submersible pumps) and can be controlled electrically. Aside from the grid connection, the investment costs are relatively low. The biggest obstacle in many developing countries is the lack of infrastructure. The cost of extending a grid is very high. Grid extension can cost between \$5,000 and \$10,000/km. Otherwise, grid-connected pumps require only a simple control box with a power breaker to control the motor, the water level, and the pump. Maintenance costs are usually very low as long as the system is designed properly. The motor and the pump should be properly matched, and the controller must be able to handle voltage fluctuations. An integrated water-level control system must be installed to keep the pump from running dry.

The investment costs of such systems depend on the cost of the grid extension and on the size of the transformer used. Usually power from a high-voltage, grid-power transmission line is not used for small pumping systems due to the high cost of the step-down transformer. The operating cost depends mainly on the electricity tariff. High electricity tariffs contribute to high pumping costs.

Wind Pumps

Mechanical Wind Pumps (Windmills)

Wind pumps operate by mechanical or electrical means, using a wind energy source. Mechanical wind pumps, known as windmills, have been used since the early 13th century for draining polders in the Netherlands. Small wooden windmills have been used also in France, Portugal, and Spain for pumping seawater to produce salt. The American windmill, made of steel, with a multi-bladed, fan-like rotor, became the most popular water-pumping technology. It was introduced between 1860 and 1900 and was used to supply water to the railroads and for domestic uses. It became very popular when millions of cattle were being brought to the North American Great Plains. During the last 100 years, more than 8 million windmills have been manufactured in the United States alone, and the design has proven so successful that the technology has been copied around the world. Today more than 1 million windmills are estimated to be in use, mostly in the United States, Argentina, and Australia. However, traditional windmills are much less efficient than modern wind turbines, because the blades are not true airfoils, and the overall operating efficiency is only about 4%–8%.

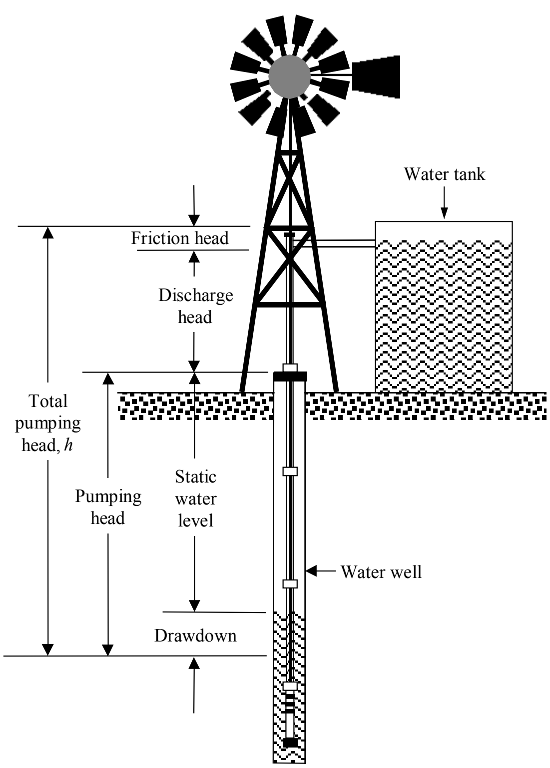


Figure 3.2. A schematic diagram of a windmill with a piston pump.

Basically, a windmill uses a reciprocating pump, a piston pump, or positive displacement pumps located below the borehole. For these types of pumps to start pumping, the wind pump crank needs to exert sufficient force on the pump rod to lift the weight of the pump rods, the piston and the water in the piston, and to overcome the friction. The amount of water delivered by the pump for a given pumping head depends on the diameter of the pump and the wind speed. A large-diameter pump delivers more water. However, the size of the pump determines the starting wind speed because larger pumps require a larger starting torque. As a rule of thumb, the size of a pump fitted to a windmill should run at approximately three-quarters of the local mean wind speed for the wind pump to run frequently enough and to achieve better water output at stronger winds. Traditional wind pumps have a rotor diameter from 2–5 m (6–16 ft). Australia's Southern Cross windmills are available up to 8 m (25 ft). According to Hodgkin et al (1987), an average rotor diameter of 7.6 m can produce 2 kW of power at 3 meters per second (m/s) wind speed. A schematic diagram of a windmill installation using a piston pump is showing in Figure 3.2.

The Australians, Dutch, and others have further developed the old American windmills through the years in terms of their weight, cost, and efficiency. As a result, several options are available today. The two major improvements in modern mechanical wind pumps include the development of a counterbalance on the weight of the sucker rod and the variable-stroke design. The other crucial development is using only 6 to 8 true airfoil blades, in contrast to the traditional windmills, which have 15 to 18 curved steel plates. By using fewer blades, the cost of the windmills decreases. These design changes make modern wind pumps twice as efficient as traditional ones.

Commercialized mechanical wind pumps are good for low wind speeds due to their high solidity rotor, which limits the piston pump speed to no more than 40 or 50 strokes per minute. The overall conversion efficiency of mechanical pumps using average wind speed is 7%–27%. Windmills are still bulky, and they need to be installed directly over the borehole so the pump rod is directly connected to the rising main and the pump. On the other hand, the best water resource is normally located on lower ground, which is a poor location for winds, so there needs to be a compromise between best wind location and best water source. For this reason, mechanical wind pumps are limited to flat plain areas.

Attempts have been made to locate the windmills further from the borehole by using remote power transmission mechanisms such as electrical, pneumatic, hydraulic, and mechanical transmissions. Using an induction generator to produce electricity, coupled with an induction motor and a pump, is the best alternative technology among these options; this will be discussed further in the next section.

Electrical Wind Pumps

Electrical wind turbines are designed to produce alternating current (AC)-or direct current (DC)-electric output and can be used to pump water by directly connecting to AC or DC motors. Electrical wind turbines are designed for low solidity rotors and are best suited for centrifugal pumps. A typical electrical wind turbine used to pump water is presented schematically in Figure 3.3. This technology eliminates the use of batteries and inverters by directly coupling the wind turbine with an AC motor, which then drives the centrifugal pump at varying speeds. This technology simplifies the problem of matching wind turbines with the appropriate water pump by varying the load electrically instead of mechanically (i.e., varying the stroke as in the case of windmills). Unlike windmills, however, this technology also solves the problem of locating wind turbines over water wells. Because wind is best at the crest of a hill, and water is found on lower ground, wind turbines can be located where the winds are strongest at the optimum-cost cable length from the well.

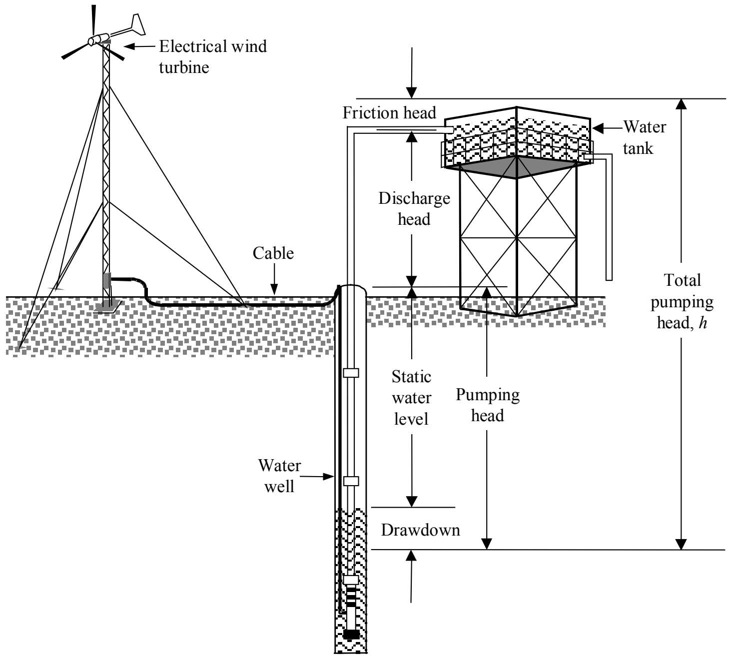


Figure 3.3. Schematic diagram of an electrical wind turbine connected to a submersible centrifugal pump.

Unlike traditional windmills, electrical wind turbines require a higher starting wind speed and perform better at high wind speeds. Electric wind pumps are twice as efficient as traditional windmills and are cost competitive compared to diesel, PV, or traditional windmills. Modern electric wind turbines have fewer moving parts than the traditional windmills and this keeps maintenance costs low. Electric wind turbines are also quite versatile.

Commercial electrical wind turbines are available from as low as 50 watts to a few megawatts. Electrical wind turbines generally require high wind speed (e.g., a small wind turbine of about 1.5-kW rated output requires an average wind speed of 4–5 m/s to start pumping). On the other hand, mechanical wind pumps can start pumping at about 2.5 m/s to 3.5 m/s. As the electrical wind turbine gets bigger, the starting wind speed needed will be higher. Generally, electrical wind turbines become competitive with windmills above an average wind speed of 5–6 m/s for water-pumping applications. Therefore, the pumping location's wind regime determines whether mechanical or electrical wind pumps will be used. Electrical wind turbines have several potential advantages over mechanical wind turbines. They are versatile: surplus electric power can be stored in batteries and used for lighting or other purposes. The wind turbine does not need to be located directly over the borehole or even near the site where the power is needed. It can be located at the best wind regime location and the power produced can be wired to the site.

Solar (Photovoltaic) Pumps

As the name implies, solar pumps are powered by solar radiation energy impinging on the surface of semiconductor materials by electromagnetic means. The smallest semiconductor material is a PV cell. Because the maximum voltage from a single silicon cell is only about 600 millivolts (mV), cells are connected in series to obtain the desired voltage. Usually about 36 cells are used for a nominal 12-volt charging system. Currently available standard PV modules range in output from less than 2 watts (W) to about 110 W. The PV module constitutes the basic building block from which any size PV array can be configured to suit the application.

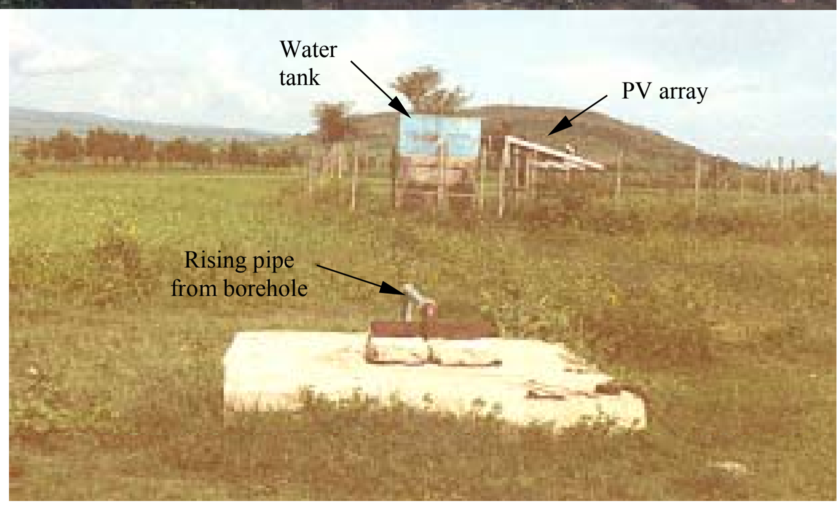


Figure 3.4. A typical village water supply using a PV pump located in Ethiopia. The system has no distribution networks.

The PV array converts the solar radiation into DC power, and this power is then used directly or indirectly (converted into AC using an inverter) to power the electrical motor to drive the pump. A typical village water supply using a PV pump is shown in Figure 3.4.

Unlike other alternative pumping options, solar pumps generally incur a high investment cost; however, this cost can be offset by a long service life since operation and maintenance (O&M) costs are minimal over its economic life. Solar pumps are a very reliable technology and can be matched quite closely to the amount of water needed. However, since solar pumps cannot deliver water on demand, a careful assessment of the solar energy resource and water demand is needed. Water tanks should be adequately designed to store enough water for days when there is little or no solar radiation.

Bio-fuel Pumps

Biogas-substituted diesel engines are a proven technology that can save 80% of diesel fuel needs in a diesel engine. This fuel is a mixture of methane, carbon dioxide, and trace gases that can be produced in a village using an anaerobic digester. The biogas produced from this digester can also be used for lighting, cooking, and heating as well as refrigeration. Field experiments have shown that this biogas can displace 80% of the diesel fuel for small diesel engines. Using biogas saves a considerable amount of money and also provides an opportunity for local employment.

The digester effluent can also be used as fertilizer. However, one cannot deny the cost of the additional labor to collect and feed the manure into the digester, the cost of organization, and the investment and recurrent costs associated with the system. O&M of such a system is slightly more than a diesel engine alone.

Another emerging technology on the market is the "Small Modular Biopower System" (SMB) technology that produces electricity and thermal energy from agricultural and forest residues. This technology has a great potential to solve the rural energy needs of many developing countries. The SMB system can use a variety of feedstocks as fuel to generate heat and electricity through advanced gasification technology. This state-of-the-art technology is being developed by Community Power Corporation (CPC), with the assistance of the National Renewable Energy Laboratory (NREL). This SMB technology is a turnkey and tar-free power system that greatly simplifies operation by eliminating any toxic effluents. The SMB system is capable of operating in a combined heat-and-power mode (CHP) to meet the electrical and thermal power needs for rural communities and small rural enterprises. These modular systems are designed for high-volume, low-cost manufacture and for ease and flexibility of operation. Figure 3.5 shows a prototype 3-kWe SMB system with its development team. This power system uses agricultural and forest residues (such as coconut shells, palm nutshells, forest slash, and corncobs) to generate electrical and thermal energy. The technology is an ideal solution for providing electricity and shaft power to solve the energy needs of rural communities and small urban areas in many developing countries.

Figure 3.5. A trailer-mounted 3-kWe prototype SMB with its development team. Photo courtesy of Community Power Corporation.

Chapter 4: Rural Water Supply Technologies

The choice of rural water supply technologies in developing countries should emphasize less sophisticated systems, with limited investment costs, and low operation and maintenance (O&M) costs. The choice of technology must focus on minimal maintenance or should be simple to maintain by the local people. However, in most cases, systems with low maintenance requirements are associated with reliable technologies, which are generally more expensive. For example, solar (PV) systems have a high initial cost, while diesel pumps have high O&M costs. There are other technologies where the investment and O&M costs are cheaper (such as hand pumps) but they are not as reliable. Hand pumps also may not fulfill the level of service required for more affluent communities. Although locals can easily maintain hand pumps, the problem with these types of pumps is the availability of spare parts. Technologies that require water treatment are not attractive for rural villages in developing countries due to the treatment cost and the unavailability of qualified technicians and needed chemicals. Various rural water supply technology options, with their advantages and disadvantages, are presented in the following chapters.

Table 4.1. Typical Daily Water Consumption for Farm Animals.

Type of Animal	Daily water consumption (liter/animal)
Dairy Cows	80
Beef brood cows	50
Horses and mules	50
Calves	30
Pigs	20
Sheep and goats	10
Chickens	0.1

The other important issue in the selection of a rural water supply technology is water consumption. Basic water needs, such as household needs (cooking, drinking, and washing), and water for cattle or irrigation are considered in the basic design criteria. Water demands for such things as fire hydrants, lawns, parks, and recreation should not necessarily be included when designing a rural water supply. Water consumption in rural areas of developing countries varies with climate, social habits, ease of access, and water quality. Water consumption in arid and semi-arid regions of developing countries is from 20-40 liters per capita per day (LCD). Twenty LCD is considered minimum and 40 LCD is on the high side. However, it is not uncommon in some places to find water consumption as low as 10 LCD. To estimate the water demand of the entire community, one has multiply the LCD by the number of people. If cattle need to be watered or if there is land that needs irrigating, an extra amount of water should be added based on the number of cattle or the amount of land. Tables 4.1 and 4.2 present the typical daily water consumption for farm animals and various crop irrigation needs. Estimating the water demand for livestock watering is similar to estimating water consumption for villages. The demand is estimated from the number of cattle and other animals and multiplied by the per-capita water consumption.

Table 4.2. Estimated Maximum Daily Water Demand for Various Types of Crop Irrigation.

Type of crops	Daily water requirement (m^3/ha)
Rice	100
Rural village farms	60
Cereals	45
Sugar cane	65
Cotton	55

Unlike water demands for human and animals, the water demand for crop irrigation is seasonal. Some crops require a large quantity of water for a relatively short period of their growing season; so all irrigation systems need to be designed for peak water demands. Generally, the water demand for irrigation varies from crop to crop. It also varies with the type of soil, soil preparation and irrigation methods, rainfall regimes, and other meteorological factors (such as temperature, humidity, wind speed, and cloud cover).

Open Wells and Hand Pumps

Village water-supply sources using open wells or hand pumps installed over the wells are generally shallow wells that can be dug by hand using a backhoe or machine. Such wells are generally from 0.5–2 m (1.5–7 ft) in diameter and up to 30 m (100 ft) deep. Dug wells can be as high as 5 m in diameter, depending on the suitability of the location and other factors. Wells dug by machines (drilled or bored) can be up to 0.75 m in diameter. However, digging a well more than 15 m deep, or even hand pumping the water from that depth, is very difficult. The well depth depends on the depth of the water table, the well recovery rate, the type of aquifer, and the size of the population using the system. The water table can be just a few feet below the surface or several hundred feet deep, depending of the geographical location and geological formation.

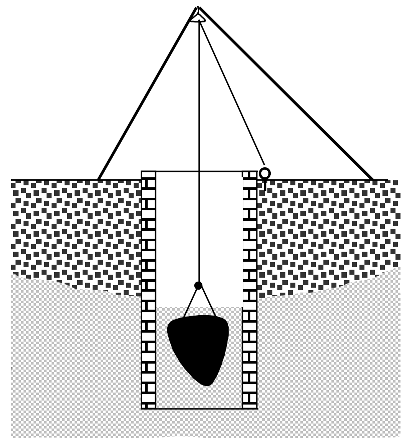


Figure 4.1. Traditional open well used to fetch water using a bucket and a pulley.

Figure 4.2. An Indian Mark II-type hand pump used in rural villages.

Getting water from an open well by using a bucket (tied with a rope and a pulley, or even without a pulley) is a common practice in many rural villages (see Figure 4.1). Such practices can be easily and economically upgraded by installing hand pumps on the open wells (constructing a concrete foundation over the open well and installing a hand pump). The well can be constructed using bricks, stones or concrete rings (similar to the ones used for municipal drainage). The concrete rings can be made with or without reinforced steels. The wall should not be built tight to allow water to enter the well. Gravel is used to filter the groundwater. Figure 4.2 shows a typical hand pump used in many rural villages. Motorized pumps can also be installed on such open wells to pump the water. Floating motor/pumps or small submersible motor/pumps are the most commonly used units for such applications. The motor (pump) should be small or pumping should be intermittent since well recovery is generally slow.

Gravity-Flow Water Supply Systems

In a gravity-flow water supply system, the water source is located at a higher elevation than the community. The water source can be a spring or a stream intake and should be capped using concrete or mesons at the source to prevent contamination of the water. Spring water quality is very high if it is capped at the eye of the spring. However, most surface water sources (both river and rainwater catchment) can be polluted by upstream users (people and animals). A water reservoir can be constructed at the source or at another suitable location, and pipelines can be laid to the village. These distribution pipelines can be communal or can be laid to each individual household. Depending on the elevation difference, pressure tanks might be necessary to control the pressure and keep the pipes from rupturing.

Gravity water systems are often preferred due to their low operating costs and simplicity. In general, properly designed gravity water systems do not require maintenance except periodically checking the pipes and faucets for leaks. Figure 4.3 shows a typical gravity-flow water supply system in rural villages, where the spring water source is capped at the foot of the mountain, and the water is piped to the reservoir and distributed to communal tap-stands.

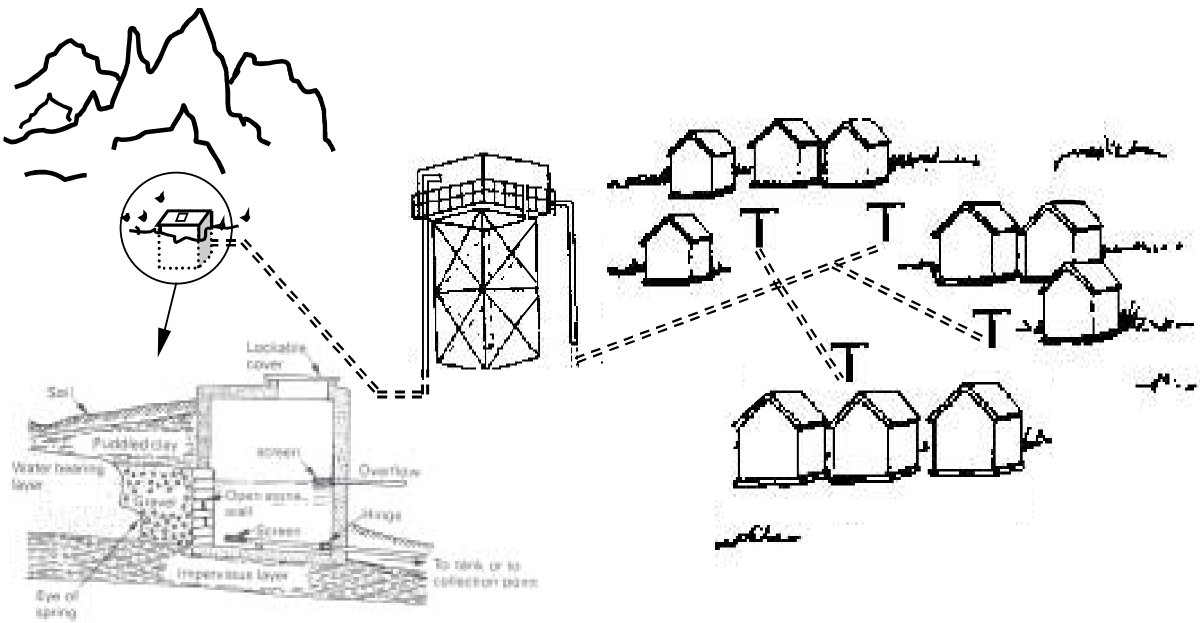


Figure 4.3. Gravity-flow village water supply system. Water tanks are generally constructed at higher locations (hilltops) or can be elevated as shown in this figure.

Depending on the availability and quantity of water, the water source can be from one or more springs or streams. Water from springs and stream sources normally decreases during the dry season. Therefore, when conducting the feasibility study, a careful water resource assessment is necessary.

Motorized Water Supply Systems

Motorized water supply systems are used when the water source is at a lower elevation than the village receiving the water. In such cases, motorized pumps are used to pump the water to the village. The water source can be a well, a spring, or a stream where the storage tank can be constructed near the water source, directly pumped to a storage tank near the village at a higher elevation, or elevated using a steel structure. Then, by gravitation, the water can be distributed to communal or household tap-stands. Motorized pumps can be operated either manually or automatically by using floating switches.

Positive displacement (volumetric) pumps and centrifugal pumps are most commonly used to pump water from surface or deep wells. Centrifugal pumps can be submersible or surface-mounted. Submersible centrifugal pumps are mainly used to pump water from deep wells; surface-mounted centrifugal pumps are used to pump water from shallow wells or from the surface. Centrifugal surface pumps include floating pumps, vertical-mounted turbine pumps, and surface-mounted centrifugal pumps. Positive displacement pumps are also categorized into two types: submersible (diaphragm) and nonsubmersible (jack, piston, and rotary vane) pumps. Figure 4.4 shows water pumping from surface water and from a deep well.

a) Centrifugal surface pump

b) Nonsubmersible jack pump (positive displacement pump)

Figure 4.4. Two types of surface pumps: a) centrifugal surface pump and b) jack pump

As the name implies, motorized water supply systems need some form of energy to run the pump. There are several options: it can be powered by grid electricity; by diesel, gasoline, or kerosene engines; or by using solar or wind energy (refer to chapter 3 for more information). For example, the pumps in Figures 3.2 and 3.3 are powered by wind, the pump in Figure 4.4(a) is powered by a small gasoline engine, and the pump in Figure 4.4(b) is powered by solar energy. Pumps in Figures 3.2 and 4.4(a) are driven by the mechanical energy produced by a windmill and a gasoline engine, respectively, while the pumps in Figures 3.3 and 4.4(b) are driven by the electrical energy produced by a wind turbine and a PV array, respectively.

Other Water Supply Systems

Rainwater is another source of water for rural villages. Rainwater can be collected either from gutters or by using a large rainwater catchment area in an open field (ponds). However, pond water is exposed to contamination, depending on human and animal activities surrounding the area. Another cause of contamination is water stagnation. Water collected in a pond has no outlet, unless the water is used for irrigation and canals are dug to bring the water to the fields. Stagnant water is a breeding place for most waterborne diseases (microorganisms such as bacteria, viruses, and parasites), and it is not generally recommended for drinking without some kind of treatment. Unfortunately, many people around the world still use untreated pond water for drinking as well as for watering cattle and irrigating fields. However, this water source is good for irrigating small fields. A simple schematic diagram of rooftop rainwater catchment is shown in Figure 4.5.

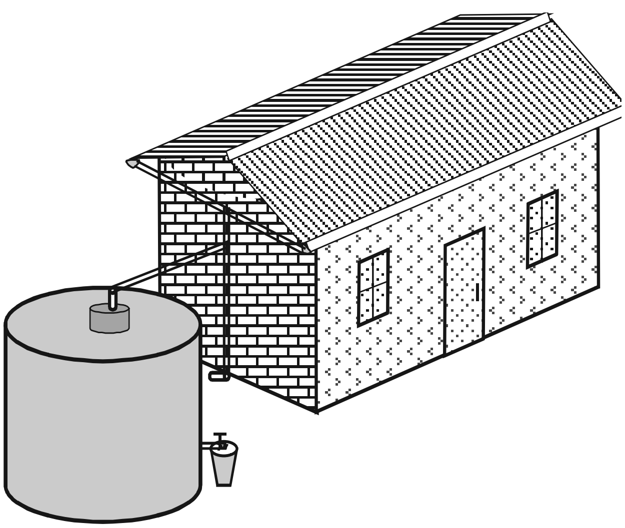


Figure 4.5. Schematic diagram of rooftop rainwater catchment

Rainwater collected from roofs can be safe to drink if the water is flushed for a while until the roof is washed clean and an intake filter arrangement is made. However, such an option should only be considered when the rainfall is adequate or when other sources, such as wells or gravity systems, are not feasible (either technically or economically). Rainwater catchment might be more suitable for individual households, where every household needs to set up the system individually. However, such a system requires galvanized roofing with gutters, piping, and a water tank.

Water Treatment in Rural Areas of Developing Countries

Most rural water supplies in developing countries do not use any type of water treatment. There are several reasons for this. One is that springs and groundwater sources are not typically exposed to contamination. Although pathogens are mobile in groundwater that flows though fractured rocks, they have a short lifespan in an aquifer, so groundwater is generally safe. However, shallow wells (dug by hand) can be contaminated at the time of construction and lack proper drainage. Before using the well water for the first time, the water should be disinfected and the well itself should have a proper drainage system in place. Installing a hand pump into shallow wells, rather than using the water directly from the open well, makes the water supply much safer if a proper drainage system is constructed. In many developing countries, chlorine is used to disinfect the raw water source and destroy pathogens during the construction of hand-dug wells (hand pumps).

Secondly, water treatment in rural villages is not sustainable. The local people have little understanding of waterborne diseases, they lack qualified technicians to operate or maintain the system [including the amount of chemicals (mostly chlorine) to apply and how much to apply], and they don't have the money. Third, in many rural villages, the quantity of water is more important than the quality. The rural people in arid regions of developing countries search for any water source, which is frequently difficult to find, and consequently they are more exposed to infectious diseases related to personal hygiene caused by a lack of water. In such cases, the availability of adequate water is more important for survival than its quality. In a country with limited financial resources, where supplying water for people and their cattle is critical, water treatment is considered secondary. Hygiene education can promote increased awareness of waterborne diseases. Most water development organizations focus on providing an adequate quantity of water from the best available source.

In most rural areas, the main microbiological and biological contamination comes from pathogenic and nonpathogenic organisms. Pathogenic organisms are nonfecal coliform bacteria found in soils. These organisms mainly cause diarrheal diseases. Fecal coliform bacteria are primarily nonpathogenic and reproduce in the intestines of warm-blooded animals. According to the WHO standard, nonfecal coliform is permitted at ratios of up to 10 numbers per 100 ml in nonpiped water supplies, but no fecal coliform is permitted. Other contaminants are organic and inorganic constituents. Inorganic constituents include such minerals as arsenic, cadmium, nitrate, lead, fluoride, and sodium, which occur naturally in groundwater or surface water, but may also result from industrial activity and agricultural practices. For example, nitrate concentrations in groundwater are usually the result of nitrogen fertilizers. Organic compounds, such as benzene chloroform, carbon tetrachloride, and DDT are more complicated and an effort should be made to protect the water source from such contamination.

Other constituents of water are radioactivity and aesthetics. Radioactivity is primarily caused by natural sources, usually in groundwater sources. Except for radon, treating water for radioactivity is too expensive for developing countries. On the other hand, certain constituents in water, such as dissolved solids, iron, calcium, and magnesium, can affect the test, odor, and usability of water. Dissolved solids, such as salts, can affect the taste and can also retard the efficiency of water disinfection processes. Calcium and magnesium make water hard.

In rural areas, water is disinfected by using a chlorine solution (made from high-test hyphochlorite powder or liquid bleach). Urban water treatmentwater treatment systems use chlorine gas. Chlorine in solid form (tablets) is mainly for individual home use.

The simplest method of disinfecting water is pasteurization by simply boiling it. However, boiling water consumes lots of fuel. According to the World Bank Report, more than $50 million per year is spent in Jakarta, Indonesia, alone for fuel to boil water in households (Burch and Thomas 1998). There are also advanced disinfection methods, such as ozone, UV disinfection, and others. These other methods will be discussed in chapters 5 and 7.

Chapter 5: Water Purification Technologies

Traditional Water Treatment Methods

Water in a natural environment that passes through a ground aquifer below 3 m (10 ft) is generally considered by many hydrologists to be completely filtered (Campbell 1983). Most artificial filters are direct imitations of this natural filtration process. Depending on the raw water quality, some of these systems work better than others. To select the best suitable treatment system for the desired application, it is necessary to understand the advantages and disadvantage of all the possible options.

The treatment selection will depend on several factors, such as affordability, population size and water demand, chemical contents of the raw water source, water source type, availability of treatment chemicals, and geographical location. Depending on the quality of the raw water source, the treatment needed may be expensive. On the other hand, if the daily water demand is smaller, simple slow sand or compact filters can be suitable. Some of the most popular water treatment options and their advantages and disadvantages will be discussed the following sections.

Traditional Groundwater Treatment

Unlike surface water, groundwater is purified by passing through the aquifer and is generally safe to drink. However, in some areas, the groundwater contains minerals, such as iron, manganese, salt, fluoride, and other substances, which causes an undesirable taste and odor. In that case, surface water may be unavoidable.

On the other hand, there are several simple techniques available to remove minerals and salts. For example, concentrations of dissolved iron and manganese can be removed by a simple aeration technique and sand. Aeration causes the iron and manganese to become insoluble so they form fine dark sediment, which is more easily removed. It can be constructed in a simple way that does not require a motorized pump. A hand pump can be used directly to pump the mineral water into the aeration system. However, other chemicals like salt, fluorides, and nitrates are not easily removed under rural village conditions. It may require some form of chemical and settling process. For example to remove fluoride, alum (aluminum sulfate) needs to be mixed with the water, followed by a settling process. Such a chemical is not easily available in rural villages.

Household filtration

To construct a household filtration system, a simple 200-liter (50-gallon) drum or pots can be used. If using a drum, water can be added at the top, then it flows through the sand compartments and gets collected using perforated pipe at the base of the drum. A household filtration system can also be constructed using simple pots where one pot with a perforated bottom is filled with sand and put on top of another pot for clean water collection. A simple faucet can be installed to the

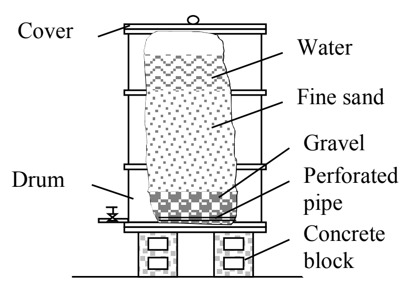


Figure 5.1. Construction of a household sand filtration system.

bottom of the pot for fetching water. In constructing a household filtration system, a layer of fine sand (about 600 mm size) should be laid on top of a layer of coarse gravel (about 30 mm size). Figure 5.1 shows a typical household sand filtration system using drums.

Slow Sand Filtration

Clay and hardpan filters are the best natural filters since they have the finest filter media. However, the finer the filter media, the slower the water passes through unless pressure is exerted as in the case of RO. Purity can also be sacrificed when water is forced to pass through the media to fulfill the demand.

Water treatment using the slow sand filtration method is the oldest treatment method and is still commonly used in many countries. Depending on the topographic location, this type of treatment may not need pumps if the water intake is at a higher elevation, and if the treatment and treated water reservoir locations are carefully surveyed. The treated water can flow by gravity to the distribution system. However, in some cases a booster pump might be needed to pump the treated water to a reservoir at a higher elevation. Figure 5.2 shows a typical schematic diagram of a slow sand filtration system.

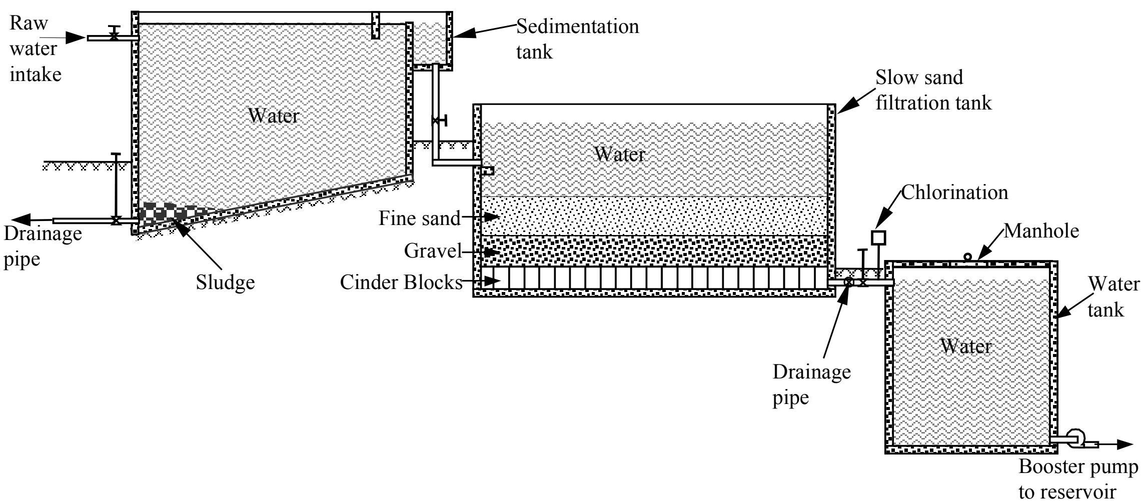


Figure 5.2. Schematic diagram of a typical slow sand filtration system.

Although the slow sand filtration process considerably reduces the amount of waterborne diseases, one cannot be sure of the amount of microorganisms that still pass though the slow sand filter, so some kind of disinfection is also necessary. Chlorine gas or chlorine solution (made from high-test hyphochlorite powder or liquid bleach) can be used for disinfection. Electric power might be necessary at the treatment plant for running the dosing and booster pumps. It is also possible to feed disinfection chemicals by gravitation to the point of application.

Treating water using a slow sand filtration system requires a sedimentation tank and a slow sand filtration tank. The sedimentation tank helps remove the suspended materials and reduce the suspended solids from the raw water. Once the concentration of suspended solids is settled and the floating materials and scum are removed, the water is guided to the slow sand filter where the remaining particles and most of the pathogenic microorganisms will be filtered out. Generally, slow sand filters can remove 99.9% of the pathogenic microorganisms.

The sedimentation tank serves as settling basin and roughing filter. The size of the tank depends on the raw water quality. The sedimentation tank should be long enough to detain the particles for a long enough period. A drainage pipe is required to remove the settled particles (sludge) and for maintenance purposes. A sedimentation tank may not be necessary if the raw water quality (in terms of turbidity) is reasonably good. The slow sand filtration tank is arranged so that an under-drainage system (usually cinder blocks) is laid at the bottom of the tank. Then come layers of gravel that begin coarse and gradually turn finer. On top of the gravel, a sand bed is laid. The thickness of the gravel layers and the sand bed also depends on the raw water quality. Once the water is guided to the slow sand filtration tank, all the particles passed from the sedimentation tank will be left on the top of the sand bed and the filtered water passes through the gravel pack and is then guided to the clear water tank.

Designing water treatment plants depends on mainly on the raw water quality and the amount of daily water demand. A slow sand filtration system is not recommended for highly turbid water, since dirt will very often clog the sand bed and interrupt the treatment process, leading to water shortages. Therefore, this treatment method is recommended for less brackish water and for small-to-medium water demands.

The maintenance required for a slow-sand filtration system is mainly on the filter tank. This is separate from the maintenance required to fix any pipe leakage or the chemical feeder units. The surface of the sand bed needs periodic raking and scraping. New sand should be added after approximately 50 cm (20 in) of sand has been scraped from the surface.

Slow sand filtration is one of the cheapest water treatment options for medium-sized community water supplies. Depending on the location of the water source and the community, such filtration systems can operate at zero power demand. If the water source is higher than the community and a better intake location is identified, the system may not require a pump. However, in many cases, a booster pump is installed to pump the treated water.

Compared to conventional water treatment methods, slow sand filtration is the simplest, the easiest to operate, but requires high maintenance, than any other water treatment method. The system does not require chemicals except for disinfection. However, this method cannot be used for communities that have large water demands because the filtration process happens naturally through gravity. A more conventional water-treatment method is recommended for large water supplies because the treatment can be forced to increase water production.

Conventional Surface Water Treatment

Conventional surface-water treatment is the most commonly used method in developed countries and in cities and urban areas of developing countries to remove materials and suspended solids in water. This is the most effective method for removing many potentially harmful water contaminants, including microorganisms, suspended sediments, and inorganic materials. The processes in the conventional surface water treatment include coagulation, flocculation, sedimentation, filtration, and disinfection. The chemicals used in these processes are coagulants, coagulant aids, and filtration aids. These chemicals have a very low toxicity and low concentration. Chemical disinfection is necessary after any of these processes for municipal water and wastewater treatment. The different types of disinfection chemicals, along with their efficiency and side effects are presented in the next section. Figure 5.3 shows a schematic diagram of a conventional water treatment plant.

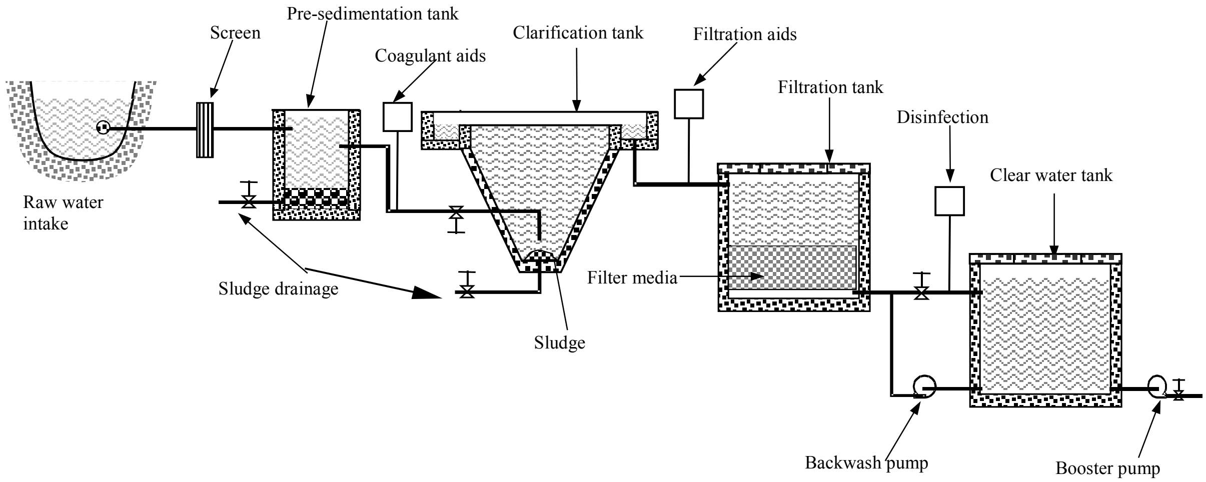


Figure 5.3. Schematic diagram of a typical conventional water treatment plant. A single tank (clarification tank) is shown in this diagram for coagulation, flocculation, and sedimentation processes.

In conventional surface-water treatment plants, raw water from rivers or lakes (or dams) will be guided through a simple screen that removes floating objects and suspended particles to prevent pipes from clogging or being damaged. In some cases, pre-sedimentation tanks are arranged (AWWA 1984) before the raw water enters the coagulation tank to remove sand and silts, especially in the case of rapid-flowing river water sources with high turbidity. In the coagulation tank, coagulant chemicals will be added to destabilize colloidal particles that would otherwise be suspended. These chemicals will alter the physical state of dissolved and suspended solids to facilitate their removal by sedimentation and filtration. The most common coagulants are alum (aluminum sulfate), ferric sulfate, lime, ferric chloride, and synthetic polymers. Natural coagulants, such as the roots of *maerua pseudopetalosa* can be superior to the conventional coagulant aluminum sulfate (Niewoehner et al 1997). Activated silica, a complex silicate made from sodium silicate and charged organic molecules (polyelectrolytes), can also be used to enhance coagulation. Sometimes polyelectrolytes are also added after flocculation and sedimentation as an aid to the filtration process. Flocculation and sedimentation are purely physical processes. During flocculation, the chemically treated water in the coagulation tank is stirred gently to increase inter-particle collisions and promote the formation of large particles. Once the flocculation process is done, the large particles formed settle by gravitation into the sedimentation tank. The resulting effluent is sent through the rapid filtration tank to separate the remaining suspended solids.

There are several ways of designing coagulation, flocculation, and sedimentation processes. Each process can be designed as separate tanks or as a single tank. When these three processes are arranged in one tank, it is sometimes called a clarification tank since the main purpose of these processes is to clarify the water. In some cases, the coagulation and flocculation processes are designed in one tank, with the sedimentation process in a separate tank.

The rapid filtration tank is sometimes called a pressure filter tank because pressure is applied to force the effluent through the filtration media in the filtration tank. The filtration media can be sand, anthracite coal, bituminous coal, limestone chips, plastic pellets, and even pieces of garnet (a semi-precious stone). These filter materials are inert, do not react with water, and are not consumed during treatment. Rapid filters generally consist of 60–90 cm (24–36 in) of 0.5- to 1-mm-diameter filter media. Particles are removed as water is filtered through the sand or anthracite filter media at rates of 40–245 liter/min/m^2 (1 to 6 gallons/min/ft^2) (Drinking Water Health Effects Task Force 1989). Rapid sand filters are most commonly used in developing countries.

All of these processes remove many of the contaminants and turbidity. Once the water has been clarified and most of the contaminants have been removed, the disinfection efficiency is improved and it will be easier to remove the remaining waterborne diseases during the disinfection process. Ninety-nine percent of asbestos, 97%–99.9% of giardia lamblia, and 30%–70% of trihalomethanes (THMs) formation potential will be removed by these processes (Drinking Water Health Effects Task Force 1989). Many of the dissolved organic and inorganic compounds will already have been removed during the coagulation process. According to Drinking Water Health Effects Task Force (1989), 60%–98% of total coliform, 76%–83% of fecal coliform, 58%–99% of giardia muris, 40%–96% of turbidity and 88%–95% of viruses (e.g., poliovirus and coxsackievirus) will be removed during the coagulation, flocculation, and sedimentation processes. Forty percent to 98% of total coliform and 10%–98% of viruses (poliovirus and coxsackievirus) will be removed during the filtration process. Filtered water, after disinfection, will contain total coliform and fecal coliform of less than 1/100 ml; and turbidity and asbestos will be less than 1 Nephelometric Turbidity Unit (NTU) and 0.5 million fibers/liter, respectively. Traditional and advanced water disinfection methods for conventional water treatment plants will be discussed later.

Other Water Treatment Options

Desalination

The main source of fresh water is solar desalination. In nature, solar desalination produces rain when solar radiation is absorbed by the sea and causes water to evaporate. The evaporated water rises above the surface and is moved by the wind. Once this vapor cools down to its dew point, condensation occurs, and the fresh water comes down as rain. This process is shown in Figure 2.1. This same principle is used in all man-made distillation systems.

Seawater desalination for a water supply can be achieved either through thermal energy, using phase-change processes, or by using electricity to drive the membrane processes. Solar energy is one of the most abundant energy sources for desalinating seawater. Desalination using thermal processes (phase-change) can be accomplished using vapor compression (VC), multiple effect distillation (ME), multistage flash distillation (MSF), freeze separation (FS), and solar still methods. The simplest and most popular method of desalination using the thermal process is a solar still. Solar stills can be constructed in many ways. Figure 5.4 shows one type of solar still arrangement. Desalination of seawater could also carried out using VC or FS using an electrical energy source.

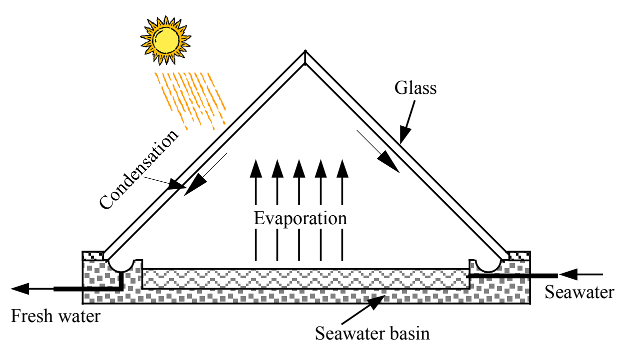


Figure 5.4. A simplified schematic diagram of a solar still.

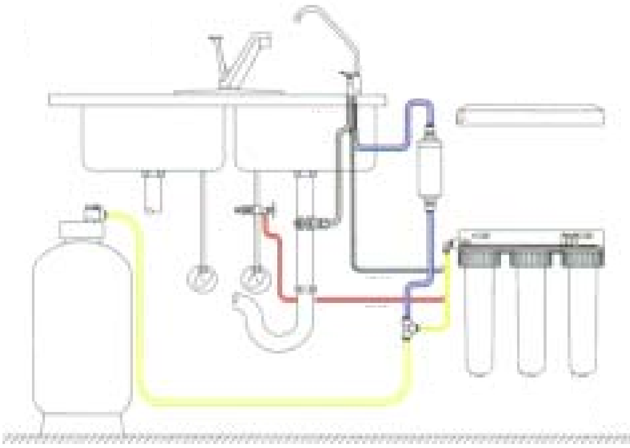
Other desalination processes that use electricity are RO, electrodialysis (ED), and ultra- and nano-filtration. These desalination processes are also called membrane processes because membranes are used in the process. In the electrodialysis process, salts are drawn through membranes leaving the salt-free water behind; in reverse osmosis, salts are left behind while the salt-free water passes through the membranes. These two processes will be further discussed in the following sections.

Reverse Osmosis

RO is basically a physical process used for purifying water. The RO unit is used to remove salt and brackishness from drinking water. It is particularly beneficial to those on sodium-restricted diets. RO can remove 98%–99% of sodium chloride, sodium carbonate, sodium sulfate, calcium chloride, and calcium carbonate from incoming water.

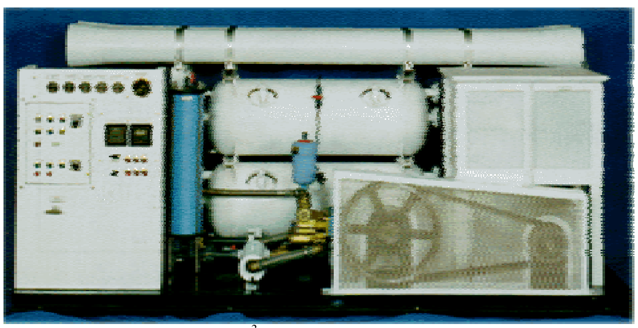
The efficiency of the RO process generally depends on the water pressure. The higher the pressure, the better the performance. Generally, RO is a very slow process because water molecules must pass individually through very small pores in the membrane. For this reason, RO is mostly used for individual home use to further increase the quality of tap water for drinking purposes, and for small water demands, such as health clinics in rural villages. However, as the technology develops, more efficient RO systems are being developed, and RO systems are currently available from small to large capacities (capable of purifying a few liters of water per day to several thousand cubic meters for conventional water supplies) (Kalogirou, 1997). Multiple RO units are used to increase the water supply capacity. Presently, large RO water supply systems are widely installed in the United States (Cook, 2000). These systems are becoming economically viable and give superior quality water using pre-filter(s). Pre-treating the raw water is necessary before it contacts the membrane to avoid fouling (the membranes are very sensitive to both biological and non-biological fouling). Figure 5.5 shows several RO systems that are designed to purify tap water in developed countries and those designed for large water supplies. Figures 5.5(a) and (b) are schematic diagrams of a small RO unit connected to a kitchen sink and the enlarged photo of the unit, respectively. Figure 5.5(c) is a medium-sized RO system available from 20–200 m^3/d. Figure 5.5(d) shows a large RO system (15,150 m^3/d) installed at Marco Island, Florida (Kadaj, 2000).

The RO process can remove 80%–98% of most toxic minerals and organic chemicals, except radon and chlorine. However, although microorganisms are much larger than the membrane's molecule-sized pores, the pores are not uniform enough to ensure removal of all the microorganisms and cannot be used for water disinfection alone. During the RO treatment process, a thin membrane is used and this membrane has pores that can pass water molecules. When water pressure forces the water molecules through the membrane, larger molecules of pollutants are left behind and washed away. Unlike most filters, the RO membrane does not accumulate any pollutants because the pollutants are constantly washed away. However, the RO membranes sometimes fail prematurely. For example, bacteria in the water can damage and shorten the life of cellulose composite membranes, while high levels of dissolved minerals (TDS) can slow down the treatment. Therefore, testers are generally provided with the RO units to check the membrane performance. Membranes of large desalination systems also need backwashing to help lengthen the system life. In most cases, the membranes need to be replaced every 1 to 3 years. The normal output of RO systems is about 500-1,000 liters/day/m^2 of membrane, depending on the amount of salts in the raw water and on the condition of the membrane.



(a) Schematic diagram of micro RO units (Micro-line) connected to Kitchen sink. Courtesy of CAI Technologies Inc.

(b) Enlarged photo of a micro RO unit for individual home use. Courtesy of CAI Technologies Inc.



(c) Medium-sized (20-200 m^3/d) seawater desalination plant. Courtesy of Environmental Equipment Consulting & Production Inc.

(d) Large RO water purification plant (four each a million gal/d capacity). Courtesy of American Engineering Services Inc.

Figure 5.5. Various reverse osmosis systems for both home use and large water supplies.

Membranes are generally made from cellulose acetate (CA) (sometimes, called cellulose thin composite organic membrane [CTA]), or thin-film (inorganic) composite (TFC) materials. The CA membrane is made of organic cellulose and can fail due to bacteria contained in the water. Therefore, the CA membrane works best for treating pre-chlorinated water since chlorine kills bacteria growth and extends the life of the membrane. On the other hand, bacteria do not effect a TFC membrane. However, TFC membranes cannot be used to treat chlorinated water because chlorine will damage this membrane and shorten its life. In this case, granulated activated carbon or extruded carbon block filters are used to remove the chlorine from the water. CA membrane technology has been in use for many years, and the TFC membrane is a relatively new technology. TFC performs better than CA and also lasts longer. Both CTA and TFC do not remove significant amounts of radon and chlorine from the water; an activated carbon pre-filter is used to accomplish this.

RO systems are the proven water-treatment technology for brackish water and for desalinating seawater. The technology is also successful in removing nitrate, radium, uranium, many inorganic substances, and several organic compounds. As the cost of the technology decreases, its use will undoubtedly increase rapidly, even in developing countries.

Solar energy using PV modules is the most suitable power source for RO, especially for remote locations. Energy recovery turbines (generally called energy recovery RO systems) can be integrated with the RO system to recover the brine energy (using a suitable brine turbine), allowing the system to be economical for a large water-supply application.

Electrodialysis

As discussed earlier, ED is another type of desalination process that draws salts through membranes by transferring ions using electrical potential difference and leaving the salt-free water behind. The dissolved salts are separated into positively charged sodium and negatively charged chlorine ions, moving under influence of electric field through membrane to opposite charged electrode. Special membranes are used to separate the electrodes to form salts.

ED is more economical for low salinity and brackish water (not more than 6,000 parts per million (PPM) of dissolved solids). Similarly, the ED process is not suitable for water of less than 400 PPM of dissolved solids because the energy requirement increases due to low conductivity. Solar energy using PV modules is an ideal power source for the ED process in remote locations.

Water Disinfection Options

Most Common Disinfectants in Use for Conventional Water Treatment Plants

The most common disinfectants used in water treatment processes are chlorine, chloramines, chlorine-dioxide, and ozone. The most common disinfectants—chlorine, chloramines, chlorine-dioxide, and ozone—are typically added immediately after filtration; however, chlorine and chloramines are sometimes added just before filtration to prevent slime growth in the filter media. Ozonization is almost always performed after filtration. The term “post-disinfection” is used to describe disinfection after filtration. The term “pre-oxidation” is used when disinfectant chemicals are used at the beginning of the treatment process.

UV light, pasteurization, silver treatment, and iodination are also used for disinfection. However, these disinfection methods are not commonly used for large water supplies because of their high cost and other factors. However, UV is becoming more popular, especially for village water supplies and for health clinics in many developing countries. There are also other emerging disinfection methods: They are photocatalytic disinfection and other advanced oxidation processes called mixed-oxidant gases. Photocatalytic disinfection is still in a trial period, but the mixed-oxidant disinfection method is more promising because of its effectiveness and because no hazardous chemicals are used or produced. These disinfection methods will be discussed later.

Pre-oxidation chemicals, like chlorine, are generally used to disinfect, remove odorous compounds and sulfides, reduce coagulant demand, oxidize iron and manganese, and prevent biological slimes and algae from forming during the treatment process. When used during pre-oxidation, chloramines are much less effective than chlorine at removing tastes and odors and oxidizing other substances that react with an oxidizing agent. Generally, the amount of disinfectant used during post-disinfection is much smaller than that used for pre-oxidation because upstream processes (in the clarification and filtration tanks) have reduced the oxidant demand.

Chlorine (gas or liquid chlorine solution, sometimes called sodium hyphochlorite) is commonly used for post-disinfection in developing countries. In developed countries, chloramines, chlorine dioxide, and ozone are also used for post-disinfection. However, many developed countries are shifting from chlorine to other alternatives to avoid the formation of by-products.

The most widely recognized chlorine by-products are THMs, which carry a toxicological risk. According to a study made by the United States Environmental Protection Agency (EPA), the term "total trihalomethanes" (TTHMs) is used in the EPA's regulation (Drinking Water Health Effects Task Force 1989). The TTHM refers to the sum of chloroform, bromoform, bromodichloromethane, and dibromodichloromethane, which are the most common THMs found in chlorinated water.

On the other hand, using chloramines, chlorine-dioxide, and ozone will avert the formation of THMs. However, studies made of these disinfection options show that there is the potential of organic by-products forming. Although there have not been many studies made on the potential formation of organic by-products from the use of chloramines, chloramines are generally weaker oxidizing agents. However, there was a great deal of concern in the past over chlorine dioxide whose chlorine residual can result in the same by-product as free chlorine. But, high-purity chlorine dioxide, which is currently available on the market, does not contain residual chlorine. However, there is still some health concern with high-purity chlorine dioxide's inorganic by-products—chlorate and chlorite ions.

Ozone is the most reactive oxidant of all used in water treatment. It has a greater germicidal effectiveness against bacteria and viruses than chlorine (Campbell 1983). It also reduces iron, manganese, lead, and sulfur concentrations in water and eliminates most tastes and odors. However, like chloramines, there is still relatively little information about possible organic by-products.

Application methods for disinfection chemicals vary depending of the state of the chemicals. Chlorine gas is normally stored in a pressurized cylinder with a special feeder attached to the knob of the cylinder so the right amount of chorine gas is fed to the system. However, chlorine solution (hyphochlorite) is fed using a dosing pump or by gravitation (a drip chlorinator). In a drip chlorinator, the chlorine solution is stored in a small container raised to a certain height to get enough pressure from the feeding point. As an alternative, the small container can sit on the water tank.

The chemical dosage amount for disinfection depends on the raw water quality. Raw water with high ammonia and natural aquatic humus content normally requires a higher dosage to oxidize. According to Drinking Water Health Effects Task Force (1989), 0–25 mg/l of chlorine, 0–1 mg/l of chlorine dioxide, or 0–15 mg/l of ozone is required for pre-oxidation; and 0.5–3 mg/l of chlorine, 0.5–4 mg/l of chloramines, 0.2–1 mg/l of chlorine dioxide, or 0.2–1.5 mg/l of ozone is needed for post-disinfection.

Chlorine gas can be very dangerous and should be kept in a separate room with a shower arrangement in case there is a cylinder leak. Chlorine solutions should also be prepared very carefully.

Ultraviolet Light

Water disinfection using UV light works by using a special type of UV lamp. A very thin layer of water passes by the lamp, where each drop is exposed to the UV light. UV light is very effective in killing bacteria; however, UV is less effective for untreated water. For example, tiny particles of mud (turbidity) can shield bacteria from the UV light, which can then escape before being destroyed. Similarly, the presence of iron in the water can interfere with the UV light transmission. Microorganisms that have hard coverings, like giardia cysts also cannot be killed by using UV disinfection (Ingram 1991). The other problem with UV light disinfection is that UV lamps lose their strength over time and it is difficult to know the effectiveness of the UV unit without taking a water sample. Figure 5.6 shows a 60-W 15 l/min (4 gal/min) prototype UV water-disinfection unit developed at the Lawrence Berkeley National Laboratory. This unit can be powered by an electric grid, a car battery, or a PV system using a 120 VAC, 220 VAC, or 12 VDC voltage source.

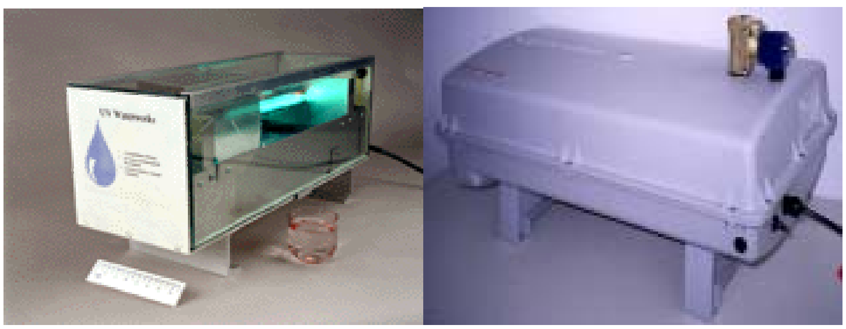


Figure 5.6. A 60-watt 15 l/min (4 gal/min) UV water disinfection unit developed at the Lawrence Berkeley National Laboratory, U.S DOE .

Solar radiation plays a significant role in the natural disinfection of all surface water. Direct solar radiation from the sun is potentially the simplest and least costly means of disinfection for village water supplies. Radiation in the ultraviolet spectrum deactivates bacteria in the top layers of exposed water by penetrating cell boundaries and affecting the cell's ability to divide. However, effective deactivation of bacteria decreases with increased depth and turbidity of the water. A parabolic trough solar concentrator with a receiver tube (e.g., a counter-flow heat exchanger) is relatively simple design and reliable technology for purifying drinking water in rural areas. A PV pump can be integrated with the system to pump the disinfected water to the water tank. This solar disinfection method was tested at the Florida Solar Energy Center (Anderson and Collier 1996) and produced up to 2,500 m^3/d of safe drinking water using a 28-m^2 solar concentrator. Others also tested the level of solar disinfection using open trays (Alward et al 1994, and Alward and Kandpal 1996).

Pasteurization

Another way to provide clean drinking water is by pasteurization. The pasteurization process heats the water to a temperature high enough to kill bacteria, viruses, and other water-borne pathogens (Andreatta 1994). There are several methods for pasteurizing water using solar radiation. The simplest is the solar box cooker, where a blackened container is used to pasteurize the water. The other method uses a heat exchanger where water can be heated above 65°C (150°F). This process destroys all pathogenic organisms, and the heated water is collected in large containers to meet the peak demands. However, this disinfection method is still not ready to be used for conventional water supplies or even to village scale; it is still in household level.

Silver Disinfection

Although silver is considered poisonous, disinfecting water using silver is safe. Concentration of PPM of 0.03 is more than enough to destroy almost all microorganisms, including pathogenic viruses (Campbell 1983). However, silver reacts with organic matter like iron, sulfur, and other chemicals, which decreases its germicidal efficiency; therefore, water must be pre-treated before using silver as a disinfectant. In addition to the concerns about chemicals interfering with the silver, silver disinfection also requires a longer contact time than chlorine. Silver filters also need frequent backwashing and replacement. Silver disinfection is mainly used to further treat home tap water instead of as a disinfectant in conventional water treatment plants.

Iodination

In many ways, iodine disinfection is similar to chlorine, but it is very expensive. According to Campbell (1983), iodine is 20 times more expensive than chlorine, but iodine is more efficient than chlorine, even at higher p^H (up to 10). Chlorine loses its effectiveness at higher p^H. Presently, iodine is used to disinfect drinking water for home use and for drinking water in NASA's space missions.

Other Water Disinfection Options

Mixed-Oxidant Gases Generated on Demand

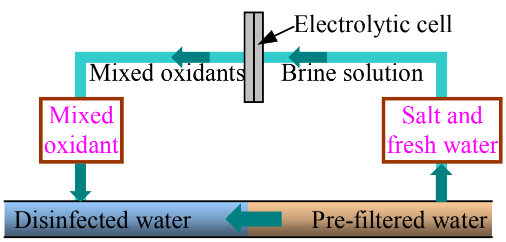


Figure 5.7. Schematic diagram of the mixed-oxidant gases generated on demand process.

This technology is the most complex of any discussed in this book. Although there are a few hundred systems installed in the field, this technology is still new. Mixed-oxidant generators are emerging as the next generation in the water treatment industry. This disinfection method is one of the most effective in destroying bacteria and viruses (99.99%) and rapidly oxidizes iron, manganese, and hydrogen sulfide. The process does not use or produce any hazardous chemicals, which makes it safer than chlorine alone. The system uses sodium chloride (NaCl) brine to electrolytically generate a mixed-oxidant solution. Assuming a dosage of 4 mg/l, roughly 3.6 grams of salt is required to produce enough disinfectant for a one cubic meter of water (Burch and Thomas 1998). Figure 5.7 shows the schematic diagram of the process. Using this method, the disinfected water will have some residual chlorine, which is enough to store the treated water for more than a week. According to the MIOX Corporation (at http://www.miox.com/miox9.htm), the mixed-oxidant solution can last up to nine days when stored in a closed reservoir and when the TTHM produced is reduced by 50%–80% over the traditional chlorination method. This disinfection method also eliminates complaints about the chlorine taste and odor.

The oxidant solution must be injected at a high enough concentration to satisfy the oxidant demand of the water, effect the desired degree of disinfection, and to meet the standard for disinfection residual. The concentration of the mixed-oxidant solution is determined by the size of the generator and the individual water system.

Although highly skilled maintenance personnel are required to maintain the electrochemical system (which includes maintaining dosing valves, venturi ducts, flow meters, and handling caustic chemicals, requiring between 25 and 80 hours per year) (Burch and Thomas 1998), operating the system does not require a qualified person. In comparison, membrane process technologies require additional maintenance to clean and replace the membranes every few months, which makes it an unattractive alternative for village water supplies. For this mixed-oxidant technology, salt can be supplied a few times per year and stored, and the salt quality does not have to be as high as the density gradient systems (membrane technologies). On the other hand, in case of membrane technologies, poor quality salt can cause the membranes to fail.

There are several different designs for oxidant solution generation technology, and the energy consumption for a unit volume of water depends on the desired dosage of the oxidant solution. The higher the dose, the lower the flow rate of the treated water or vice versa. These types of disinfection systems can be powered by a PV array, a battery, or a grid power source. In general, the technology is relatively easy to install and operate, and is suitable for larger rural villages (more than 100 people)

Photocatalysis

Several studies have been conducted on photocatalytic processes to treat wastewater with photo-oxidation technologies using a large variety of chemicals to destroy toxic and hazardous chemicals. The feasibility of using sunlight in conjunction with the photocatalytic process to destroy organic water pollutants was demonstrated in the mid-1980s. Later, the U.S. DOE, through NREL and Sandia National Laboratories (SNL) made efforts to develop the solar detoxification technology for commercial application in the early 1990s, and NREL completed negotiations and signed an agreement with International Technology Corporation (ITC) (Mehos et al. 1994). This process has demonstrated its effectiveness against organic chemical pollutants, including agricultural pesticides. However, these processes are new technologies and are still at the development stage.

Research performed at the University of Florida and other places (Cooper et al 1997 and Zhang et al 1994) has shown that using this technology with a solar energy source is effective for the bacterial decontamination of a water supply. Titanium dioxide (TiO_2) has been shown to be photocatalytically active in the presence of sunlight. It is also the most widely used photocatalyst for the simultaneous disinfection and detoxification of water. At a UV spectrum of 300-400 *nm,* 3% to 4% of the solar energy is used for organic photo-destruction due to its high catalytic activity, its stability in acidic and basic media, and its non-toxicity (Vidal 1998). Photocatalytic oxidation (using UV light in conjunction with TiO_2) generates hydroxyl radicals. The hydroxyl radical is a short-lived, extremely potent oxidizing agent, capable of oxidizing organic compounds. According to the work of Cooper et al (1997), a 0.01% concentration of TiO_2 can reduce benzene, toluene, and xylene to below detection levels after 4 hours of 50 W/m^2 solar radiation. Similarly, water contaminated with *Escherichia coli*, *Pseudomonas aeruginosa*, *Serratia marcescens*, and hydrocarbons can be disinfected after 4 hours of contact time with a 0.01% TiO_2 concentration.

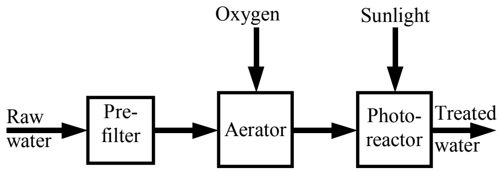


Figure 5.8. A schematic diagram of a solar water detoxification system.

A solar water detoxification system uses a photocatalytic process with a complex series reaction. The most common design for this system is a parabolic trough concentrator that focuses sunlight on a clear glass tube as a receiver. The near-UV portion of the solar spectrum in this photo-reactor activates the TiO_2 catalyst to produce hydroxyl radicals. The hydroxyl radical will attack virtually any organic compound and break organic pollutants into nontoxic materials such as carbon dioxide and water. Figure 5.8 shows a schematic diagram of a solar water detoxification system. In this system, pre-filtering is necessary to remove any particles that might accumulate on the reactor walls or on the catalyst. Once the water is pre-filtered, oxygen is introduced using an aerator to make sure there is enough dissolved oxygen to have a complete reaction of the organic contaminants.

Other Issues Related to Water Purification

Some other issues that need to be discussed related to water purification are the effect of incoming water temperature, the alkalinity and acidity of treated water, the toxicity of coagulant residuals, and the health risk associated with disinfection.

Incoming Water Temperature

Hot incoming water has a positive effect on water purification for certain treatment processes. For example, an incoming water temperature of about 37.7°C (100°F) is most efficient for UV systems and gets less effective as the temperature lowers (Campbell 1983). Similarly, a high incoming temperature increases the disinfection process in chemical disinfection (e.g., chlorine disinfection).

p^H Scale

Knowing the level of alkalinity and acidity in the water supply is crucial to controlling corrosion or scale build-up in the distribution pipes and in the purification process. Corrosion and scale build-up in pipes are the main problems in water distribution networks.

The p^H scale is a measure of the acidity, alkalinity, or neutrality of the water. The p^H ranges from 1 to 14, where 7 is neutral. On the pH scale, anything below 7 is acidic and anything above 7 is alkaline. Vinegar and lemon juice are examples of highly acidic fluids (p^H = 2–3), bleach is highly alkaline (p^H = 10-14), and blood and distilled water are neutral (p^H = 7).

Corrosion in pipes starts when the p^H is lower than 6.5. The presence of dissolved minerals in acidic water increases the water's electrical conductivity. The presence of oxygen, carbon dioxide, and a higher water temperature tends to enhance corrosion. Corrosion is caused by the chemical and/or physical processes that take place in a water-treatment system due to the release of metal and non-metallic materials. Corrosion can damage pipes, pumps, and other distribution pipelines as well as water heaters, plumbing, and fixtures in buildings. The release of these metals (such as lead and cadmium) and non-metals (such as asbestos) pose serious health risks. Zinc, copper, and iron are essential nutrients for humans and are no threat to human health unless taken at extremely high levels. However, lead, cadmium, and asbestos are toxic; and the maximum allowable in drinking water, according to the EPA standard, is 50 μg/l for lead, 10 μg/l for cadmium, and 7.1 million fibers/l for asbestos (Drinking Water Health Effects Task Force 1989). Asbestos is found naturally in raw water supplies or from the corrosion of asbestos-cement pipes in the distribution system.

Similarly, water with a p^H above 8.5 will have a strong caustic taste, cause a build-up of scale, and reduce the internal diameter of pipes, reducing the pipe's capacity. Higher p^H values also slow the purifying action and reduced the effectiveness of residual chlorine in pipes. Alkaline water can coat the lamp sleeves of UV systems and retard their effectiveness (Campbell 1983). Water with very low p^H also hinders iron removal from the treatment system. Acidic water can be neutralized using alkaline-based chemicals, such as a sodium carbonate solution.

Another problem in water treatment is precipitation, when insoluble materials start settling in the filtration and distribution networks. This may clog filters, pipes, pumps and water meters, and plumbing and fixtures in buildings. Clogging reduces the amount of water the pipe can carry. The most common causes of precipitation in treated water are the precipitation of calcium carbonate (lime) and aluminum hydroxide. Such precipitation occurs when a high concentration of carbonate ion and aluminum in ionic form is present. Reducing the pH values to the point where the ionic concentration of the carbonate and aluminum is reduced can control this. Usually, precipitation of alum occurs when the p^H is either below 6 or above 8, and adjusting the p^H to 6 or 7 ahead of filtration can prevent this. Similarly, lowering the p^H value until the concentration of carbonate ions is below the level at which calcium precipitation starts to form can prevent calcium precipitation. This critical p^H depends on the Ca^{++} ion concentration and total alkalinity of the water.

Hardness

Hardness is a property of water, primarily caused by calcium and magnesium cations. Hardness is a measure of the scale-forming potential for calcium and magnesium ions. Generally, water hardness is known by its soap consumption, because no suds can be produced until the minerals causing the hardness have been combined with the soap. Some heavy metals, such as iron and manganese also consume soap. The minerals that are removed by soap remain as an insoluble scum.

Water hardness may be divided into two types: carbonate and non-carbonate. Carbonate hardness includes that portion of the calcium and magnesium that combines with bicarbonate and the small amount of carbonate present. This is usually called temporary hardness because it can be removed by boiling. Almost all of the carbonate and bicarbonate ions in groundwater originate in soils from respiring organisms, decaying vegetation and from the dissolution of carbonate rocks, such as dolomite and limestone.

Non-carbonate hardness is the difference between total hardness and carbonate hardness. It is caused by those amounts of calcium and magnesium that combine normally with the sulfate, chloride, and nitrate ions, plus the slight hardness contributed by minor constituents such as iron. Non-carbonate hardness cannot be removed by boiling. Generally, water that has a hardness of less than 50 mg/l is considered soft.

Silica is the combination of silicon and oxygen (SiO_2). Although it does not contribute to the hardness of the water, it is an important constituent of the encrusting material, or scale, formed in many groundwater systems. When deposited, the scale is commonly calcium or magnesium silicate. Acids or other chemicals that are used to chemically treat wells cannot dissolve silicate scale.

Toxicity of Coagulant Residuals

Using coagulant(s) and coagulant aids in water-treatment systems can introduce toxic substances into the treated water in the form of residuals. Some of these toxic substances are inorganic metal salts (e.g., iron and aluminum salts), inorganic and organic polymers, and sulfates. The EPA lists these residuals as secondary maximum contaminant level (SMCL). They do not cause serious health effects unless they are at extremely high levels. However, EPA sets limits up to 50 μg/l for aluminum salts, 0.3 mg/l for iron, and 250 mg/l for sulfates (Drinking Water Health Effects Task Force 1989). Although detailed investigations have not been made on the effect (absorption) of iron salts in the gastrointestinal tract, iron is considered an essential nutrient for humans. Natural polymers (starches, gelatin) are generally used as a source of food nutrition and have no adverse health effects. However, synthetic polymers are not well absorbed by the gastrointestinal tract. Natural polymers are rarely used in water treatment. The health risks of the monomer content in synthetic polymers used for treating water are still not known.

Health Risks Associated with Disinfection

The health risks caused by exposure to disinfectants and their byproducts depend on the type of disinfection chemical. Therefore, handling such chemicals should follow the guidelines given by manufacturers and health departments. For example, chlorine gas should be handled carefully and stored properly. Separate chlorine dosing rooms equipped with water sprinklers should be normally arranged for safety. Chlorine in powder form is much easier to handle than chlorine gas, although one still needs to be careful in handling, preparing, and feeding the solution using dosing pumps.

Although chemical residue is very necessary in the distribution system to control microbial growth, the amount of residue should not exceed the acceptable limit; the higher the chemical residue, the higher the chemical exposure to humans. According to Drinking Water Health Effects Task Force (1989), acceptable residual limits for chlorine is up to 1.5 mg/l; for chloramines, the level is up to 4 mg/l, and for chlorine dioxide, it is up to 0.5 mg/l. Disinfectant residuals also prevent slime formation and the subsequent degradation of the water quality in distribution piping.

As stated in an earlier section, the most widely recognized chlorine by-products are the THMs, chlorinated acetic acids, and haloacetonitriles, which have characteristics of toxicological risk. The TTHM refers to the sum of chloroform, bromoform, bromodichloromethane dibromodichloromethane, which are the most common THMs found in chlorinated water. Several studies have been done by the U.S. National Research Council (NRC), the U.S. National Cancer Institute (NCI), and other organizations to determine if there is any association between these chlorine byproducts and cancer in humans, but the studies are inconclusive. However, the NRC suggests that the levels of dichloroacetic and trichloroacetic acids (from the chlorinated acetic acids group) should not exceed 0.12 and 0.05 mg/l, respectively, in drinking water. Similarly, the NRC recommends that dichloroacetonitrile (from the haloacetonitriles group) be limited to 0.056 mg/l and that dibromoacetonitrile (also from the haloacetonitriles group) not exceed 0.023 mg/l (Drinking Water Health Effects Task Force 1989). Many studies, according to Ball (1991) show that, in general, chlorine byproducts increase the level of mutagenic activity that is detectable in bacterial and other vitro systems, although the risks are probably not high.

Generally chloramination produces less byproduct than chlorination, and all the byproducts are similar, with chlorination byproducts having a lower concentration (or weaker oxidizing agents). Chloramines can also be produced from chlorine when ammonia is present in the raw water source. However, the biggest concern was with less-pure chlorine dioxide, where chlorine residual can be produced like the same byproduct with free chlorine.

Although, the lack of residuals in the distribution network with ozone disinfection means there are no toxicological hazards, not maintaining the residual levels is a major disadvantage. Ozone is a very unstable, but effective, disinfectant for drinking water.

Improving Water Quality by Combining Purifiers

With the exception of conventional water treatment methods, most water treatment methods need a combination of purifiers. These water purification methods (e.g., RO, UV light, ED, and solar stills) all use a combination of purifiers. At the least, the raw water should be filtered before it passes through the RO, ED, and UV units. Generally, all home-use purifiers, except distillers, are always sold with combined treatment units. Distillers for home use are usually sold alone. However, a distiller alone only partially removes organic pollutants (volatiles). By simply adding a carbon filter, all pollutants can be removed. Some combinations of purifiers for home-use application are shown in Table 5.1. UV, ED, and RO units are always sold with a sediment filter to clean the water ahead of it. A carbon filter is best for trapping cysts and other microorganisms, as well as for removing additives, radon, and odors. A redox filter is best for removing toxic minerals. A bacteria filter removes microorganisms.

Table 5.1. Some of the Possible Combinations of Purifiers for Home-Use Application (Ingram 1991).

No.	*Possible Combinations*				
1	Distiller	Carbon filter			
2	Sediment filter	Carbon filter			
3	Sediment filter	Redox filter	Carbon filter		
4	Sediment filter	Bacteria filter	Carbon filter		
5	Sediment filter	Redox filter	Bacteria filter	Carbon filter	
6	Sediment filter	RO	Carbon filter		
7	Sediment filter	Redox filter	RO	Carbon filter	
8	Sediment filter	Bacteria filter	RO	Carbon filter	
9	Sediment filter	Redox filter	RO	Carbon filter	
10	Sediment filter	Redox filter	Bacteria filter	RO	Carbon filter
11	Sediment filter	UV light			
12	Sediment filter	UV light	Carbon filter		
13	Sediment filter	Redox filter	UV light	Carbon filter	

Chapter 6: Wastewater Sources and Treatment

Wastewater is a combination of water-carried wastes removed from residences and institutions, waste created by commercial and industrial activity, water from the ground, and surface water (including storm water). Wastewater sources are generally categorized as municipal, agricultural, or industrial. Municipal wastes are from residential, commercial, and institutional activities, and waste from street drainage or runoff. Commercial and institutional activities that create waste include hospitals, clinics, department stores, offices, and public recreations, to name just a few.

The contaminants in wastewater are suspended solids, nutrients, biodegradable organics, pathogens, heavy metals, refractory organics, and dissolved inorganic solids. Refractory organics include agricultural pesticides, surfactants, and phenols, which tend to resist conventional wastewater treatment methods. Heavy metals usually come from commercial and industrial activities. Inorganic solids, such as calcium, sodium, and sulfate are found in domestic water supplies. Biodegradable organics are composed of proteins, carbohydrates, and fats, which destabilize natural oxygen in the ecosystem, especially if they are discharged into lakes and stagnant waters before being treated.

Agricultural wastes come mainly from fertilizers; biomass wastes, such as cattle dung, tree branches, and vegetation fumes; and other agricultural residues. Industrial wastes are the most complex types of wastes; they can contain a wide variety of toxic chemicals, depending on the type of industrial process. Each industry normally performs its own waste treatment and chooses the best treatment type and process, depending on a combination of effectiveness and cost. Once each industry treats its wastes, the effluent can be drained to streams or rivers, while the solid waste can be disposed of in landfills. In this guidebook, only rural and municipal wastes will be discussed since agricultural and industrial waste treatments are generally more complex and are usually treated individually by the concerned premises.

Municipal wastes are wastes from cities and urban centers and include solid wastes and sewage. On the other hand, wastes in rural villages consist mainly of excreta and refuse. The excreta are mainly feces and urine, and refuse is the garbage or rubbish. This is discussed further in the section on Rural Sanitation.

Municipal solid wastes include all kinds of rubbish or garbage from residences and from commercial and other institutional centers, including food waste, papers, plastic bags, glasses, as well as harmful chemicals from hospitals and commercial centers. These harmful chemicals should be separately sorted, and disposed of with special care. In most cases, solid wastes will be put into landfills and incinerated.

Sewage is human excreta and wastewater flushed along a sewer pipe and includes wastes from kitchen sinks, baths, toilet flushes, laundries, and runoff. When we refer to wastewater treatment, we are referring to sewage treatment. Typically, domestic sewage is composed of 99.9% water and 0.1% impurities, mainly suspended, colloidal, and dissolved solids. There are also gases, microorganisms, and other materials.

Generally there are two major treatment methods used to treat sewage—stabilization ponds and advanced wastewater treatment methods. Wastewater treatment using stabilization ponds will be discussed in the section on Municipal Wastewater Treatment. Advanced wastewater treatments require capital-intensive units, often aided mechanically with concrete channels, tanks, and other devices (including screens, grit chambers, settling tanks, thickeners, aeration tanks, digesters, and other unit processes). In this method, chemicals are used to remove pathogens. These advanced methods will not be discussed in this guidebook.

Rural Sanitation

Rural sanitation is very important to eliminate waterborne diseases that are transmitted through the fecal-oral cycle. Effective rural waste sanitation breaks this cycle at the source and greatly reduces pathogen intake. However, rural sanitation by itself cannot solve the waterborne-related problems unless it is accompanied by hygiene education and a clean, safe water supply.

However, handling rural domestic wastes is usually much easier than handling urban wastes. People in rural areas are quite dispersed, and they do not require complex sewage networks or drainage pipes. Solid wastes, such as ashes from cooking, dung, and other refuse are usually biodegradable and are used in agricultural fields. The rural sanitation problem is mainly related to handling excreta and other non-biodegradable refuses. However, in the rural areas of many developing countries, non-biodegradable wastes are very rare and any waste that does occur (such as dry cell batteries) can be handled by the villagers with a simple program of health education. Therefore, this section will discuss how to handle excreta in rural villages.

In most rural areas, a simple pit latrine or some type of composite latrine is used to handle the excreta. There are number of modified designs available on the market for pit latrines and composite pits. In a pit latrine, a hole is dug, a timber or concrete slab is placed over the hole, and a shed and roof are placed around the slab for privacy. However, there is a problem with odor and flies, which a simple cover can control. The ventilated improved pit (VIP) latrine, developed in Zimbabwe, as shown in Figure 6.1, is by far the best design for rural villages because the vent pipe removes the odors and flies from the latrine. A flytrap is also very effective against flies and mosquitoes instead of using a cover over the drop hole. The flytrap can be used for the VIP as well as for the unventilated latrines.

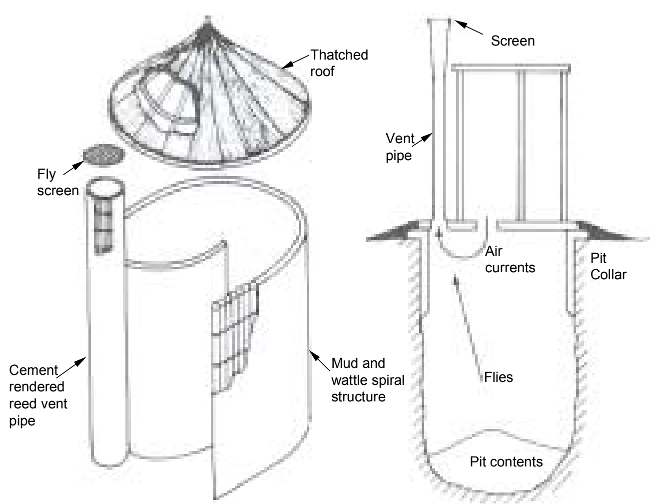


Figure 6.1. Schematic diagram of a ventilated improved pit (VIP) latrine developed in Zimbabwe.

Pit latrines have several problems. Some are associated with construction, water contamination, and the groundwater table. A rocky location is always difficult for the villagers to dig themselves; in most cases, rock-drilling machines are not available in rural areas. Similarly, a sandy-soil location is also a problem because loose soils collapse very easily while digging. Construction where the groundwater is high is also very difficult because of the danger of mosquitoes and backsplash from the pit while using the latrine. The other problem associated with pit latrines is the pollution of groundwater source, especially if drinking-water wells are located nearby. As a general rule, latrines should not be located upstream of the water source and should not be built within 15 m of a well.

The next improved pit-latrine design is the pour-flush toilet, like the one shown in Figure 6.2. This kind of toilet is designed to completely prevent the passage of flies and odors and requires very little water to flush as compared to the conventional cistern-flushed system. Flushing in a pour-flushed latrine is done manually, which makes it easier for those households that use a communal water supply. In conventional flush-toilet systems, large quantities of water are required to carry the excreta to the sewage system or septic tanks. However, in pour-flush latrines, the excreta are carried to a small soaking pit. In case of unsuitable soil conditions, septic tanks can also be used to carry the excreta. However, the sewer line should be short and have enough velocity to guide the excreta to the septic tank. Therefore, to have enough velocity, the short sewer line should have higher slope. According to Cairncross and Feachem (1983), the slope ratio should be 1:50. Generally, a two-compartment septic tank that can be shared among adjacent houses is recommended to reduce costs. The first compartment receives the flushed wastewater and after settling, the effluent goes to the second compartment. A septic tank helps separate and digest the solid wastes, while the liquid effluent flowing out of the tank is drained to a field or soaking pit. The sludge that accumulates in the tank should be periodically removed.

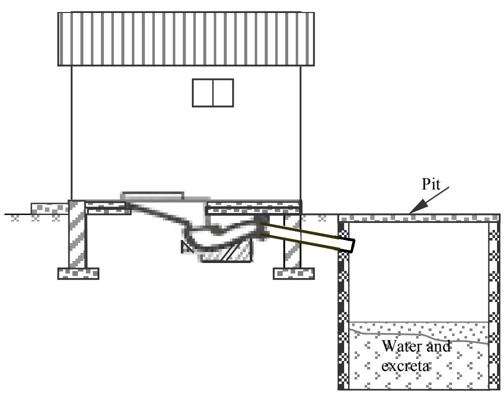


Figure 6.2. Schematic diagram of a pour-flush latrine construction.

There are several other rural sanitation systems that are not mentioned above, including cesspools, composite toilets, bucket latrines, aqua-privies, and others. Although these kinds of sanitation options are widely used, they not generally recommended.

Municipal Wastewater Treatment

In many developing countries, municipal wastes are the main public health concerns because there is no single individual responsible for these wastes except the city administration. Municipal waste management is always a big responsibility for city administrations, especially in developing countries, due to a lack of infrastructure, finances, and know-how. However, in developed countries, waste management is well organized and is mostly privatized or leased; every individual household, commercial center, and institution pays for the service. In this section, various treatment methods and their drawbacks will be discussed. However, before discussing the wastewater treatment methods, it is important to understand the characteristics of the sewage (i.e., physical, chemical, and biological).

The characteristics of sewage indicate the quality of the wastewater. The physical characteristic is the level of suspended solids: the presence of various chemicals and microbiological pollutants. The biological characteristic is the amount of oxygen required to oxidize the various organic chemicals. The oxygen demand is expressed either as a chemical oxygen demand (COD) or a biochemical oxygen demand (BOD), or total organic carbon (TOC). The measure for BOD is expressed as BOD_5 to relate to the measure of biodegradable organic matter contained in the sewage, and COD is approximately 1.5 times the BOD_5. The BOD is usually measured by keeping a sample of sewage at 20°C for five days and calculating the amount of oxygen used to oxidize the organics. The COD is measured by boiling the sewage with an acid dichromate solution, which converts most of the organics to carbon dioxide and water. The chemical characteristic of sewage is the presence of organic and inorganic constituents, nutrients, and toxic chemical contaminants.

Sewage quality is normally expressed in terms of its BOD. The strength of the BOD reflects the type of sewer and the lifestyle of the people because the BOD comes from feces, urine, and sludge. For example, BOD values of 400–800 mg/l are common in cities and towns of developing countries; in such areas, raw sewage contains approximately 40 g of BOD per person per day. In this case, if the per capita water consumption of the community is 100 l/person/day, the sewage will contain 400 mg/l of BOD (i.e. $(40 \times 10^3)/100$). Similarly, if the water consumption is lower, the BOD will be higher. However, if the sewage passes through a septic tank or some kind of settling tank (e.g., aqua-privy), approximately half of its BOD will be lost. Night soil (sewage not diluted with sludge) will clearly have a high BOD because it has no sludge (it contains only feces and urine). In such cases, the BOD of night soil may be as high as 30,000 mg/l (30 g of BOD/day and 1 l/day of liquid is contributed by each person). According to Mara (1977), the strength of the BOD is categorized as weak (up to 200 mg/l), medium (350 mg/l), strong (500 mg/l), and very strong (above 750 mg/l).

In wastewater treatment, contaminants are removed by physical, chemical, and biological means and the treatment methods are usually classified as physical, chemical, and biological processes (Metcalf and Eddy, Inc. 1979, and Steel and McGhee 1979). The physical wastewater treatment process applies physical forces. Typical physical processes are screening, mixing, flocculation, sedimentation, flotation, and filtration. Chemical treatment processes remove or convert the contaminants by adding chemicals or through chemical reactions. The most common examples used in chemical wastewater treatment are precipitation, gas transfer, adsorption, and disinfection. Chemical precipitation, for example, is accomplished by producing a chemical precipitate, which will settle at the end.

A biological treatment is used primarily to remove the biodegradable organic substances (colloidal or dissolved) in wastewater. Basically, these substances are converted into gases that can escape to the atmosphere or into biological cell tissues that can be removed by settling. Biological treatment is also used to remove pathogens and nitrogen from wastewater. In most cases, wastewater can be treated biologically.

The four major groups of biological treatment processes are aerobic, anaerobic, anoxic (the process by which nitrate is converted biologically into nitrogen gas in the absence of oxygen), or a combination of the three. The principal applications for these processes are removing carbonaceous organic matter (measured in BOD, COD, or in TOC), nitrification, denitrification, or stabilization. The most common wastewater treatment method used in many regions with hot to moderate climate regions is a stabilization pond, which is discussed in the next section. Other emerging technologies will be discussed in later sections.

Stabilization Ponds

Stabilization ponds are a suitable treatment technology because they are also very effective at removing pathogens (WHO 1987). Stabilization ponds consist of a series of ponds into which the sewage flows. Treatment occurs through natural physical, chemical, or biological processes and no extra energy is required except the sun. Such treatment methods are the cheapest and simplest of all the treatment technologies and are capable of providing a very high-quality effluent. Ponds are very easy to maintain and require no routine operation. They can absorb both hydraulic and organic disturbances and can treat a wide variety of domestic and industrial wastes. The system can be flexible and can be expanded with little investment. Stabilization ponds can also be used to convert the emitted gases into useful energy. The biogas produced from the biological processes can be collected and used to produce energy (either electricity or heat or both). The biggest disadvantage of stabilization ponds is that they take up a lot of space.

There are basically four types of wastewater stabilization ponds: anaerobic ponds, facultative ponds, maturation ponds, and a high-rated pond, which is also called an aerated lagoon or an oxidation ditch. All four types of ponds are discussed below. In practice, the first three types of ponds are basically joined in series and can have two or three stages. If one stage of treatment is used, the pond will normally be anaerobic or facultative. However, in general, a secondary pond for additional aerobic biological treatment should follow an anaerobic pond. A schematic diagram of the three stages of a wastewater stabilization pond with aerated lagoons is shown in Figure 6.3.

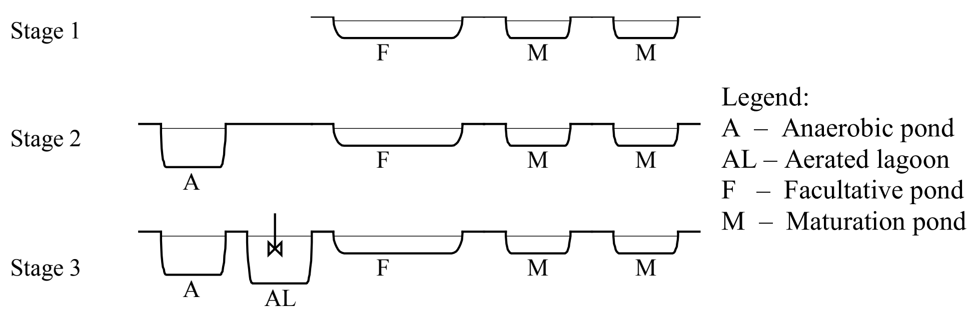


Figure 6.3. Schematic diagram of the three stages of a wastewater stabilization pond with aerated lagoons.

Anaerobic Ponds

Anaerobic ponds are basically open septic tanks used for pre-treating large volumes of strong wastes. Anaerobic digestion involves the decomposition of organic and inorganic matter in the absence of molecular oxygen. In anaerobic ponds, anaerobic digestion and settling will take place, and a thick scum usually develops on the surface. Retention times typically vary from 1–4 days, and the preferred pond depth is 2–4 m. Odor can be avoided by controlling the volumetric load of the BOD (not more than 400 g/m^3/day) and the concentration of sulfate ion in the raw waste (not higher than 100 mg/l). According to Cairncross and Feachem (1983), at 20°C temperatures, 50% of the BOD can be removed after a one-day retention, and 70% of BOD can be removed after a five-day retention period.

There are two types of anaerobic suspended-growth processes used for treating wastewater: anaerobic digestion and anaerobic contact. Between the two, the anaerobic digestion process is the most effective method for stabilizing organic materials and biological solids. It is also one of the oldest processes used to stabilize sludge. During the process, the organic material contained in mixtures of primary settled and biological sludge in anaerobic conditions is biologically converted into methane (CH_4) and carbon dioxide (CO_2). Diluted organic wastes can also be treated anaerobically. The process is carried out in an airtight tank; sludge needs to be supplied continuously or intermittently and retained in the tank for varying periods of time, depending on the quality of the sludge and the surrounding geographical conditions, such as the ambient temperature.

If digesters are used in an area where the ambient temperature is very low, such as in Canada and Northern Europe, half of the energy goes for heating and half for electrical energy (mostly for pumping but also for ventilation). However, if the wastewater treatment plant does not have a digester, heating is not required.

Facultative Ponds

Facultative ponds are a combination of aerobic, anaerobic, and facultative bacteria. Facultative processes are biological treatment processes in which the organisms are indifferent to the presence of dissolved oxygen (these organisms are known as facultative microorganisms). There are three zones in facultative ponds: (1) a surface zone where aerobic bacteria and algae exist; (2) an anaerobic bottom zone in which accumulated solids are actively decomposed by anaerobic bacteria; and (3) an intermediate zone, which is partly aerobic and partly anaerobic, in which the decomposition of organic wastes is carried out by facultative bacteria.

The facultative pond is usually the largest pond in the system, and, in the absence of pretreatment in anaerobic ponds, the wastewater flows first to this pond. On the upper layers of the pond, oxidation of organic matter takes place with the oxygen being provided by photosynthesizing algae. Sludge accumulates and digests anaerobically at the base of the pond so that sludge removal is required every 10–20 years. According to Mara (1976), the depth of the pond suggested is a compromise between the effect of excessive anaerobic activity in deeper ponds and the risk of vegetation in shallow ponds. The area is generally calculated based on the surface BOD loading rate, and this depends on the amount of sewage flow rate, sunlight, the BOD of the influent, and the ambient temperature.

Maturation Ponds

Maturation ponds are wholly aerobic and are responsible for the final stage of the BOD removal, reducing the fecal bacteria and viruses. Generally, two or more maturation ponds must follow a facultative pond (see Figure 6.3). As a rule of thumb, three maturation ponds are used with a retention time of five days and depths of 1–1.5 m. The retention time decreases as the number of maturation ponds increases, and increasing the retention time will also provide a greater chance of microbiological purification. In a warm climate, maturation ponds can remove 95% of fecal coliforms with a retention time of five days. Maturation ponds can also provide the best environment for fish farming.

The biological processes involved in maturation ponds are similar to other aerobic suspended-growth processes. Residential biological solids are endogenously respired, and ammonia is converted to nitrate using the oxygen supplied from the surface reaction and from algae. As with all biological nitrification systems, the efficiency of (low-rate) ponds decreases as the wastewater temperature increases. Normally, secondary treatment in maturation ponds will eliminate the need to disinfect effluents intended for agricultural reuse. However, to provide a reliably nitrified effluent that is low in BOD and suspended solids, an efficient and reliable effluent-treatment process is required.

Aerobic Stabilization Ponds

Aerobic stabilization ponds are large, shallow earthen basins that are used to treat wastewater by natural processes involving algae and bacteria. In aerobic ponds, the oxygen is supplied by natural surface aeration and by algae photosynthesis. The bacteria in the aerobic degradation of organic matter use the oxygen released by the algae through photosynthesis. The algae in turn, use the nutrients and CO2 released in this degradation. The main function of aerobic stabilization ponds is to further purify the effluent.

Aerated Lagoons/Oxidation Ditches

These kinds of ponds are also called "high-rate" stabilization ponds because the treatment approach is to speed up the conversion of organic wastes into algae by using a motorized aeration system.

Aerated lagoons (ponds) evolved from facultative stabilization ponds when surface aerators were installed to overcome the odors from organically overloaded ponds. If a facultative pond is too small, or if toxic substances or lack of sunlight prevent the algae from adequately photosynthesizing, the BOD will exceed the oxygen supply and the pond will turn anaerobic. In that case, it may require extra oxygen to be supplied by mechanical means. Such a method is called mechanical aeration or an aerated lagoon. When motor-driven surface aerators provide the oxygen, the lagoon develops a flocculated suspension of bacterial cells. These bacterial cells convert from organic solids to form sludge, and this sludge must be removed before the effluent is discharged or reused. Therefore, maturation ponds generally follow aerated lagoons, as shown Figure 6.3. Four days is a typical retention time and will remove 85% to 90% of the BOD. Bacterial reduction is poor, but this problem can be solved by a sufficient number of maturation ponds. Normally, the recommended depth of an aerated lagoon is between 3–4 m, with banked slopes of 1:2 (Cairncross and Feachem 1983). The banks and bottom must be protected from erosion caused by the turbulence of the aerators.

In general, oxidation ditches are very similar to aerated lagoons; the only difference is the layout and the fact that most of the sludge is recirculated. Wastes are circulated around a 1–2-m-deep oval channel at a velocity of about 0.3–0.4 m/s (Cairncross and Feachem 1983). The velocity and the aeration is provided by rotating cylindrical brushes pushing the effluent forward while at the same time providing intense turbulence. In such a method, effluent from the ditch is settled into a secondary sedimentation tank and more than 95% of the sludge from the tank is returned to the ditch. Such an approach produces a much richer concentration of bacterial flocs than would be produced in an aerated lagoon. This facilitates shorter retention times (1–3 days) and causes the sludge to be aerated for much longer periods (20–30 days) (Cairncross and Feachem 1983). Such a method helps produce a highly mineralized excess sludge that can be dried on sludge-drying beds without further digestion. BOD reduction using an oxidation ditch approach is usually good, but, like the aerated lagoons, bacterial removal is poor. However, as with aeration lagoons, maturation ponds are used for further purification.

Other Emerging Technologies in Wastewater Treatment

Renewable energy technologies, such as wind, solar, biogas, and their hybrids, with or without backup diesel generators, (Meliβ et al 1998) are very attractive methods for fulfilling the energy needs of wastewater treatment systems. Using biogas produced from the wastewater for gas generation or cogeneration is also possible and desirable. For example, a small standard wastewater treatment plant, which consists of a preliminary sedimentation tank, a trickling filter, and a secondary sedimentation tank, can be powered by renewable energy technologies. Such treatment systems could have a simple primary clarifier, a trickling filter and secondary clarifier, and a simple denitrification and disinfection system. Such systems require energy mostly for pumping or ventilation systems. For an area with excellent wind and solar conditions, a hybrid of solar and wind systems with battery backups could be an alternative source of power for wastewater treatment. Sizing the systems correctly is very important; they must be able to supply the loads even on low wind and/or solar radiation days. In this case, careful load management options and alternatives should be considered (e.g., diesel backup generators). Solar detoxification is an emerging technology, currently on the market, that can be used for the secondary treatment of wastewater (to remove trace organics and to kill bacteria and some viruses). This will be discussed in the next section.

Solar Detoxification

Solar radiation energy (direct sunlight) has been used for the biological processes in stabilization ponds. Now there are new emerging technologies for treating wastewater that use the UV portion of the solar spectrum to activate the semiconductor catalyst that produces hydroxyl radicals. As mentioned in Chapter 5, solar energy has long been used for water purification and disinfection. The same principle is used to treat hazardous wastes in water, air, and soil.

The most promising technology for destroying TOCs in wastewater treatment is the UV advanced oxidation processes (AOPs). In commercial applications, the most common AOPs utilize UV light combined with ozone (far-UV/O_3), hydrogen peroxide (far-UV/H_2O_2), or a photocatalyst to generate hydroxyl radicals (near UV/TiO_2) (Prairie et al 1995). Among these, TiO_2 is the most commonly used photocatalytic oxidant in commercial solar- and lamp-based detoxification systems. NREL also developed a heterogeneous photocatalyst that outperforms standard TiO_2 for commercial applications; however, the research has not been followed up (Blake 2000).

The oxidation chemistry and potency of the photocatalytic process of solar detoxification systems are similar to other chemical oxidation methods that generate hydroxyl radicals. Like UV/O_3 and UV/H_2O_2, solar detoxification systems can oxidize organic pollutants into nontoxic materials, such as CO_2 and water and can disinfect certain bacteria. This technology is very effective at removing further hazardous organic compounds (TOCs) and at killing a variety of bacteria and some viruses in the secondary wastewater treatment of effluents, but it is not effective at treating raw wastewater. Pilot projects demonstrated that solar detoxification systems could effectively kill fecal coliform bacteria in secondary wastewater treatment (Burch and Thomas 1998). Therefore, some kind of pre-treatment, such as stabilization ponds or conventional wastewater treatment methods (which consist of a preliminary sedimentation tank, a trickling filter, and a secondary sedimentation tank), is necessary to use this technology effectively.

Other solar detoxification systems, using a thin-film, fixed-bed reactor (TFFBR), developed without a light-concentrating detoxification system (Bahnemann et al 1997), are recommended for relatively small volumes of waste or drinking water. TFFBR is a non-light-concentrating system that uses a TiO_2 catalyst. This technology, using stand-alone PV systems, has been tested and proven to be suitable to pre-treat wastewater that will be reused or to purify polluted drinking water for small communities or individual households in Germany. In this technology, a certain volumetric decomposition of the pollutants is maintained by adjusting the flow rate on the photoreactor to the available amount of UV light. The UV sensor controls the voltage regulator that supplies the voltage to the motor pump. This technology can be used for various applications, especially in regions that have a high amount of solar radiation per year.

According to a study made by Turchi et al (1992) and Link and Turchi (1991), cost projections of solar detoxification systems are comparable to those of conventional technologies such as carbon absorption and electric-lamp-powered, UV light/H_2O_2 systems.

Chapter 7: Appropriate Technology Assessment

Appropriate technology usually refers to technologies that are relatively cheap, simple to design, easy to mass-produce, readily available, easily maintainable, and so on. It is the technology that fits the circumstances and is thus appropriate. That is, the technology must be appropriate in terms of cost; it must be appropriate in performance so it can fulfill the intended purposes; and it must be simple so it can be operated and maintained by locals. A good engineering solution involves the sensitive application of basic principles to a particular problem so a solution is derived that is genuinely appropriate to the local context.

However, the term "appropriate technology" is often confusing. For many people, the term implies only technologies that can be used everywhere in the developing world. But appropriate technologies have no boundaries. There will be always certain appropriate technologies that are suitable to certain locations. A technology that is appropriate for one location may not be appropriate in other locations. The appropriateness of any technology depends on several factors. Some of them are:

- Affordability
- Availability of energy resources, skilled labor, fuel, and spare-parts
- Suitability to the local geographical features
- Favorability of the local conditions
- Suitability to the local needs
- Infrastructure to the technology
- Performance
- Suitability of the technology and cultural habits.

The needs of developing countries are so enormous that governments cannot afford to fulfill the basic needs of its people. Therefore, affordability is one of the main issues in selecting a technology. On the other hand, the affordable technology should be suitable to the local needs and conditions. In most cases, the local conditions influence the selection of the technology. For example, when designing and constructing a water-supply system, in most cases, the local conditions will dictate the type of technology that is selected. The water source determines the kind of water treatment and/or pump required for the water-supply system.

Lack of a basic infrastructure (e.g., roads, availability of nearby maintenance stations, skilled labor, and spare parts) may lead to choosing a simple technology that only fulfills the minimum requirements. The availability of energy resources (e.g., solar and wind) is crucial when using PV panels or wind machines. In remote locations, the availability of fuel could be a problem. Other factors, such as the suitability of the technology (from a simplicity point of view) and traditional habits, also influence the choice of technology. The following sections will assess the selection of appropriate technologies for various water supply systems and water sources.

Water Resources Assessment

Identifying a proper water resource is always a big challenge in water-supply systems. Very often, selecting the water source is not given enough attention when designing the water supply systems: identifying the right water source determines the cost of the system. Water source selection should be made based on the affordability of the water-supply system unless there are no alternative water sources. In many cases, it is not uncommon to find only one alternative source. The other important factor in selecting the water resource is the availability of enough water to fulfill the community's water demand. This is always a problem for designers. In many cases, the only groundwater source may not be sufficient to meet the demands of big towns and cities. Surface water sources, such as rivers or lakes, may require laying several kilometers of pipelines in addition to the cost of the water treatment. A surface-water resource may not be attractive for village water supplies due to the high investment and O&M costs. However, in developing countries, groundwater sources are generally the cheapest option for village water supplies.

Depending on the village income level, hand pumps, gravity-flow piped spring water sources with communal or household taps, or wells with motorized pumps could be the best alternative water supply for villages. Hand pumps are good to pump water from shallow wells up to 30-m deep for individual and small community use. Gravity-flow, piped-water supplies can supply small to large communities, depending on the quantity of the water source. Motorized units include pumps powered by diesel generators, mechanically driven diesel/gasoline/kerosene engines, or pumps powered by solar or wind energy.

Identifying and selecting the water resource requires an in-depth understanding of the socio-economics of the end users, the quantity and quality of the raw water, the infrastructure of the area, and the social acceptability. In a socio-economic study of the area, one has to understand the community's ability to operate and maintain the system in addition to the initial investment costs. The water resource should be enough to supply not only the current demand but also the near-term projected water demand. In most cases, the quality of the raw water will determine the type of water-supply system selected, which in turn determines the investment and recurrent costs of that system. Surface water is usually turbid and requires treatment, leading to high operating costs due to the requirement of chemicals and qualified operator(s). Similarly, groundwater contaminated with organic and inorganic metals and other chemicals might need a sophisticated water-treatment system. The infrastructure of the area is another factor that influences the investment costs and the type of water-supply system. Therefore, the water resource should be technically and economically viable and socially acceptable.

Water Supply Technologies Assessment

Rural Water Supply

It is very important to choose a water supply technology that can work under the existing construction and operating conditions. More importantly, it must work under the prevailing maintenance conditions. For example, a water treatment plant generally requires a certain level of attention and skills to operate that may not be available in small villages. It is always more preferable to find a good quality water source and protect it from pollution than it is to take water from a polluted source and treat it. Similarly, motorized pumps should be installed where adequate arrangements have been made to maintain the system.

Cheaper and simpler technologies require less maintenance and are more reliable in practice. They can also be repaired at the village level. However, the availability of the water source usually determines the appropriateness of the technology for a rural water supply.

Rainwater collected from corrugated sheet roofs can be relatively pure. However, most rural village houses are not corrugated sheet roofs, and collecting rainwater from thatched roofs is a problem. Rainwater usage is also affected by the rainfall pattern. Rainwater is seasonal, and it is neither economical nor hygienic to construct large storage tanks that can provide water for the rest of the season. However, rainwater catchment could be used to supplement other water sources.

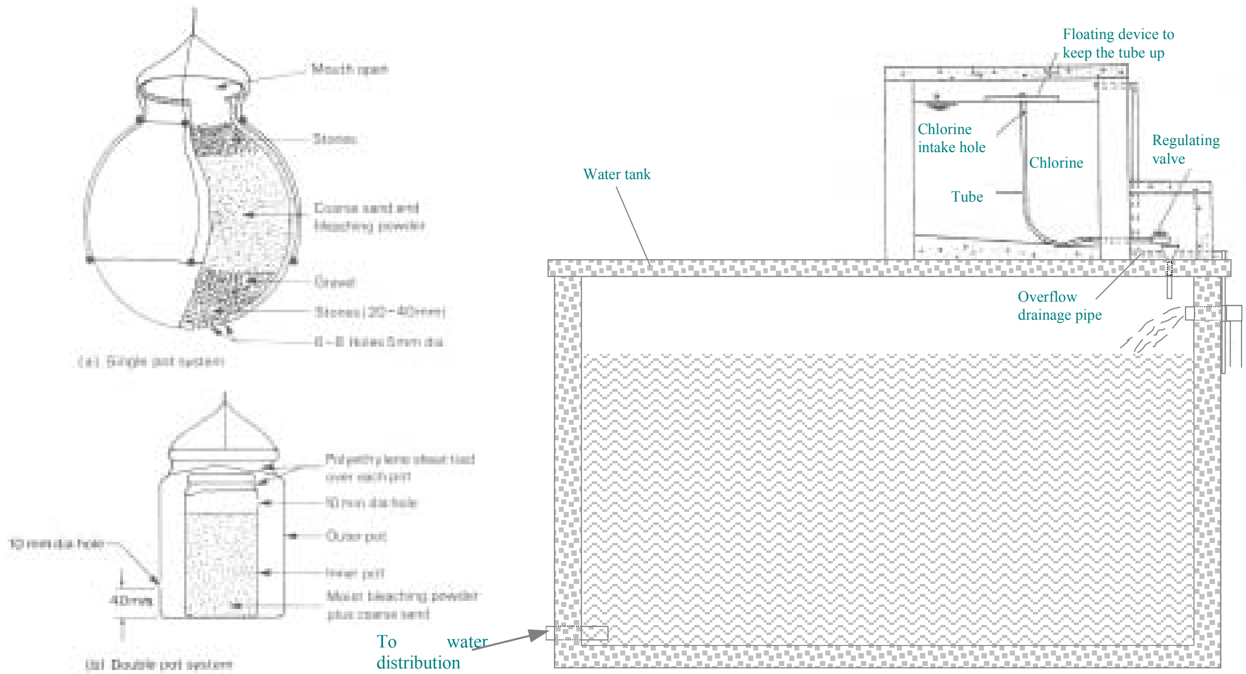
In most cases, surface water may be readily available and easy to collect but is generally polluted. In sparsely populated upstream areas, streams may be reasonably clean and safe enough for domestic use. In most cases, however, streams, rivers, lakes, and ponds are exposed to human and animal activities. But using conventional treatment plants for rural water supplies is not reliable for several reasons. There is a lack of skilled labor, spare parts are not readily available, and they require a continuous supply of treatment chemicals, which most rural communities cannot afford. However, using simple household filtration or slow sand filtration technologies can provide adequate treatment for rural water supplies (see Chapter 5).

Groundwater is preferable to surface water if the water can be extracted easily. Spring water is the best source for a rural water supply if there is adequate quantity. In most cases, a gravity-flow spring water supply is the cheapest and simplest system, and the maintenance is also the lowest. However, if the spring catchment is located at a lower elevation than the villagers' residence, the water might need to be pumped, or the villagers will need to walk to the nearest distribution point.

Well water is another option for rural water supplies. If the community can afford it, and if the well is deep enough to require it, motorized pumps or hand pumps can be used. In some cases, well water can be drawn up using some kind of vessel with a simple pulley-and-rope mechanism. However, open wells are generally exposed to pollution and are not recommended. Sealing for contamination during flooding will reduce the pollution.

The main cause of water contamination in a rural water supply, other than at the source, is at the storage tank. Rusty water tanks can contaminate water, by leaky pipes, or in home storage jars. Other possible contamination is caused by poor drainage at the mouth of the well. This is a very common problem, especially in hand-pump installations, since water is delivered right on top of the well. On the other hand, most contamination in the household is caused by poor hygienic practices, and this can be controlled through education.

One solution to the problem of rural water supply contamination is using a simple chlorinator for disinfection. Chlorine can be added to the well, to the main water storage tank, or in households either manually or with a pot- or drip-chlorinator, as shown in Figure 7.1. The pot chlorinator can be a single or double jar.



a) Single and double pot systems *(Pickford 1977)*. b) Drip chlorinator system.

Figure 7.1. Typical chlorinators used for disinfecting a rural water supply.

Distributing water to individual households may not be affordable in a rural village. An alternative solution is to provide water at public water points, also known as communal tap-stands. In such cases, the design of the tap-stands should depend on traditional water-carrying methods. For example, tap-stands should have a platform at shoulder height for those people who carry water in buckets on their head. Communal shower and clothes-washing facilities should be included in the design. Proper drainage is crucial for effective use of the facilities. Drainage problems are usually caused by heavy use of the facilities where vandalism (like breaking of taps) can occur due to frustration, and the surrounding facility could be muddy. This area is a breeding spot for mosquitoes and/or other waterborne diseases. The area should be paved with concrete and have proper drainage.

Urban Water Supply

In developing countries, the technology used for urban water supply is similar to what is used in developed countries, although slightly less advanced and less complicated. However, water supply systems can vary from one place to another, depending on the water quality, quantity, and local conditions. The design and construction of water-supply systems also varies from country to country.

Town water supplies require larger water sources, and groundwater may not be sufficient to fulfill the demand. In this case, surface water could be the most likely source (although groundwater can be used to supplement). Most surface water in developing countries is turbid from silts and soils; in developed countries, the water might contain effluents from industries. Therefore, technology selection should be based on the water resources and other local conditions. Local conditions need to be considered when selecting technology. Can the local end users afford to maintain and sustain the system? The equipment should not be so sophisticated that the local operators cannot understand it. The technology should be appropriate so the system can be easily operated and repaired without assistance from other places.

Conventional water treatment plants are the most commonly used technology for urban water supplies. Conventional treatment plants contain sedimentation (settling), coagulation, flocculation, filtration, and disinfection processes. Depending on the water resources and other local conditions, the conventional treatment system can be designed in a simplified or a complex way. In some cases, part of the process can be omitted or combined, depending on the water resource. For example, a simple settling tank can be used to remove heavier particles before the water enters the clarifier, or the settling tank can be integrated with the clarifier to reduce the treatment cost, depending on the water quality. Coagulation, flocculation, and sedimentation processes can be done in a single clarifier tank. Clarifiers can be designed with an upward flow or spiral-flow. Coagulant chemicals, like alum (aluminum sulfate) is most commonly used to cause small solid particles to form large clusters, called flocs, which settle faster in the clarifier. Figure 7.2 shows a horizontal-flow settling tank and an upward-flow clarifier. There are also upward-flow sedimentation tanks (usually in circular form), and they are more efficient and compact than horizontal-flow tanks. However, upward-flow tanks are more expensive than horizontal tanks. On the other hand, horizontal-flow tanks are easier to construct. The spiral-flow clarifier/settling tank is the most expensive of all, and is mainly used to treat the most heavily silted water.

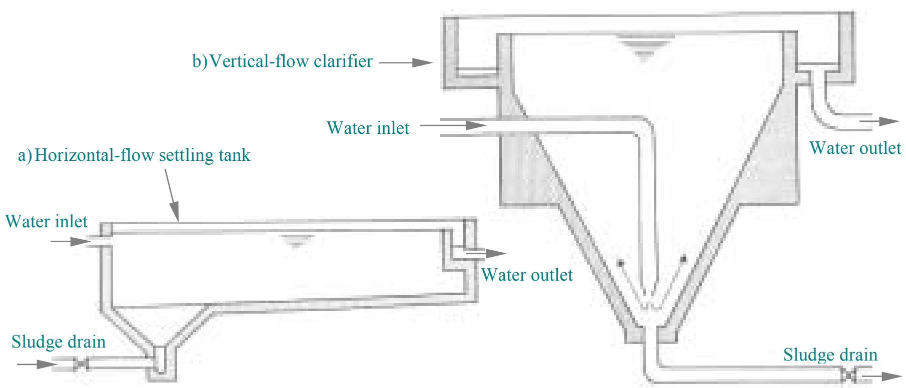


Figure 7.2. A typical horizontal-flow settling tank and an upward-flow clarifier.

There are two types of filtration processes in treatment: the rapid sand filtration and slow sand filtration process. (The process is explained in Chapter 5). The rapid filtration process requires some kind of pressure for the water to be driven through the sand bed and requires frequent cleaning using forced water or air followed by water, called "backwashing." On the other hand, in a slow sand filtration process, water is passed through the bed by gravity. Slow sand filtration is not recommended for large water supplies because the filtration process is slow. If they are used, large-area, slow-sand filters are required to fulfill the demand, which may not be practical in issues like cost and land space. Once the water is treated, it needs to be disinfected to kill bacteria and other waterborne diseases. (See Chapter 5 for the most commonly used disinfecting chemicals and their applications).

To be sustainable, the technology should be designed to suit the local conditions and to fulfill the needs of the end users. Depending on the local infrastructure, affordability, and the size of the community, the treatment plant can be designed in simplified form (e.g., a combination of a simple pre-sedimentation tank followed by a horizontal-flow settling tank and a slow sand filtration system with a simple chlorine solution for disinfection) or to the most complex process combination. Depending on the raw water quality, most advanced treatment plants will have a pre-sedimentation tank, followed by either an upward-flow or radial-flow clarifier and a rapid sand filtration system. Chemicals like coagulant and filtration aids should be added to speed up the coagulation, flocculation, and filtration processes. A pre- and post-chlorination is also necessary for disinfection. Other disinfection chemicals, like chloramines, chlorine-dioxide, and ozone are also used for disinfection to reduce the risk of chlorine byproducts in many developed countries. UV light, pasteurization, silver treatment, and iodination are also used for disinfection (see Chapter 5 for further reference).

Emerging Technologies

Water for domestic water supply purposes should be clean and safe; and, other than groundwater sources with no hazardous chemicals and contaminants, all water sources should be treated. However, water treatment is a costly business and requires treatment and disinfection chemicals.

There are several alternative water treatment technologies that are as effective as the traditional water supply technologies mentioned for both rural and urban applications. Some of these technologies are designed to avoid the need for treatment and disinfection chemicals; others require pre-filtered water to disinfect, while still others require only disinfection. For example, salty and brackish water can be treated by using either phase-change and membrane processes (see Chapter 5). Phase-change processes generally use thermal energy; some of these processes are solar stills, freeze separation, vapor compression, and various distillation methods. Some membrane processes are RO and ED, where electric power is required to treat the water.

Other disinfection technologies are UV light, pasteurization (thermal disinfection), photocatalysis, and mixed-oxidant gases. The UV disinfection system can be either solar- or lamp-driven. The solar-driven UV systems are not effective because treatment is done at ambient temperatures, which requires long exposures to kill viruses. However, this kind of system could be effective if heat is applied in addition to the solar radiation energy. On the other hand, the lamp-driven UV disinfection system, shown in Figure 5.6, is more effective as long as the water is not turbid. This kind of system can be powered using renewable or conventional energy systems. UV systems are generally used for small applications, and mixed-oxidant gases are potentially useful for large water supplies.

These emerging technologies are designed to operate based on their specific area of application, either independently or with a combination of purifiers. For example, a health clinic's needs include sterilization, distilled water, cooking, and hot water. The most appealing technologies could be solar thermal hybrid systems.

But the cost of these emerging technologies and the power required to operate them are still more expensive. Nevertheless, every technology has its own best area of application, and technology selection should be made based the appropriateness of the technology to the local conditions.

Wastewater Treatment Technologies Assessment

Selecting the appropriate technology for wastewater treatment depends on several factors. Some of the factors are the community lifestyle (city, town, or rural village), its socio-economic condition, the infrastructure of the area, the geographic location (hot or cold climate), quantity and quality of wastewater, and other factors. The characteristics of the waste indicate the kind of lifestyle. The level of the BOD reflects the type of sewer and the lifestyle of the people. A high

BOD shows the community's per-capita water consumption is low because BOD comes from feces, urine, and sludge. Conversely, a low BOD shows a high per-capita water consumption, such as in cities.

Waste treatment is categorized into two groups: rural sanitation and municipal wastes. Municipal wastes in cities and urban centers include solid wastes and sewage. Sewage waste treatment, depending on the factors listed, can be treated using the traditional stabilization ponds or using advanced wastewater treatment methods. As discussed in Chapter 6, advanced types of wastewater treatment require capital-intensive systems, often aided mechanically with concrete channels, tanks, and other devices, including screens, grit chambers, settling tanks, thickeners, aeration tanks, digesters, and other unit processes. These methods require that chemicals be used to remove pathogens. This treatment method is recommended for countries that are economically strong and have a cold climate. For countries with a hot climate, however, stabilization ponds are recommended. They are an inexpensive and proven technology for wastewater treatment. Solar detoxification could be used if further treatment of trace organic compounds and bacteria is required to reuse the effluent.

In rural sanitation, the waste is mainly excreta and refuse. The excreta are mainly feces and urine, and the refuse is garbage or rubbish. There are several ways of handling these wastes, and most of them are listed in the rural sanitation section of Chapter 6. However, the improved, ventilated pit latrines could be better at controlling odor and the flies for poorer communities, while a pour-flushed latrine with a small soaking pit or septic tanks can be used for communities with a higher income.

Renewable Energy Resources in Water and Wastewater Treatment

Renewable energy technologies have long been used for water-supply applications. They can be used to pump water from wells or to power booster pumps as well as for water-treatment systems. Renewable energy sources can provide power for traditional or conventional water treatment technologies as well as new emerging technologies (UV disinfection, desalination plants, and distillation, direct heat, or photocatalytic oxidation to destroy pathogens).

Renewable energy sources, such as solar, wind, biomass, and bio-fuel-related sources are becoming more attractive for water supply and wastewater treatment applications. Solar energy can be used either directly or indirectly (thermally or electrically) to pump or treat water and wastewater. Solar thermal energy can be best utilized for desalination of salty or brackish water, pasteurization, various methods of distillation, or indirectly even for water pumping applications. PV-produced electricity is one of the simplest technologies to pump water. PV is suitable for powering desalination plants (e.g., RO and ED systems), UV systems, and many other applications.

Solar energy is particularly important in treating wastewater. Direct solar radiation is used for wastewater treatment. The three most common wastewater treatment methods are stabilization ponds, aerated lagoons, and oxidation ditches (refer to Chapter 6 for details).

Solar detoxification using chemicals in conjunction with biological treatment is another effective approach. Chemicals are added to increase the performance of the treatment plant. Hydroxyl radical, called TiO_2, is a powerful oxidizing agent that can attack virtually any organic compound and is used as a catalytic treatment in solar wastewater detoxification.

Similarly, wind energy can be used to either pump water mechanically (using windmills), or the electricity produced from the wind turbine can be used to pump, treat or disinfect water. Mechanical wind pumps (windmills) operate at lower wind speeds compared to electric wind turbines. Windmills start pumping at speeds between 2.5 and 3.5 m/s, while electrical wind turbines need an average wind speed of 5–6 m/s to become competitive with windmills for water-pumping applications. However, the starting wind speed gets higher as the size of the wind turbine rotor increases. On the other hand, electrical wind turbines have several advantages over windmills because of their versatility and electricity generation. The turbine can be located at a higher wind regime, and the power produced can be wired to the pumping site. The electricity generated from the turbine can be stored in batteries or used for water purification systems. Some areas where wind turbines can be used are water pumping, lighting, and for water purification systems (e.g., UV (lamp-driven) and desalination systems).

Biogas can also be used for pumping water in rural villages. The biogas produced from biomass digesters (methane) is also suitable for cooking and lighting as well as being used as fuel for water pumping. The other popular biogas fuel is ethanol, which is becoming more popular for fueling vehicles. Bio-fuels are a proven technology that can save up to 80% of the fuel needs in a diesel engine. A new emerging biomass technology is the development of SMBs that can use any agricultural residues to produce electricity or thermal heat. This technology can power water pumps, water purification systems, or even fulfill the entire power needs of small- to medium-sized villages and urban centers. Presently, this technology can provide up to 100 kW of power and will be available in large capacities in the future (see Chapter 3 for further reference).

Hybrid systems are also becoming more attractive these days, especially for remote standalone applications. A hybrid system can be a combination of PV, a wind turbine with or without a backup generator, and battery storage.

However, in promoting any renewable energy technology for water treatment in rural villages, one must consider issues like system sustainability, costs, availability of energy resources, skilled manpower, and spare parts. Using renewable energy technologies for water treatment, especially desalination plants, can be very expensive. The process demands a lot of energy, which is a high investment cost, especially for rural applications. On the other hand, renewable energy sources can be more viable options for certain treatment needs and locations. For example, grid power may not be an alternative source for remote locations of many developing countries and islands because of high grid extension. In such cases, renewable energy sources might be the only alternative solutions. Therefore, every alternative system must be evaluated based on the local conditions and system sustainability issues.

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Glossary

Activated carbon – A highly adsorptive material used to remove organic substances from water.

Activated silica – A coagulant aid used to form a denser, stronger floc.

Aerobic – A process that takes place in the presence of air or oxygen.

Algae – Primitive plants, one- or many-celled, usually aquatic and capable of photosynthesis.

Alum – The most common chemical used for coagulation. It is also called aluminum sulfate.

Anaerobic – A process that takes place without air or oxygen.

Anoxic – The process by which nitrate is converted biologically into nitrogen gas in the absence of oxygen.

Aquatic – Living in water.

Aquifer – A formation or group of formations or part of a formation that contains sufficient saturated permeable material to yield economical quantities of water to wells and springs.

Artesian well - A well deriving its water from a confined aquifer in which the water level stands above the ground surface. It can also be water that is forced from the aquifer by compaction caused by the weight of overlying sediments.

Biodegradable – Capable of being broken down by biological processes.

Bit – Cutting tool attached to the bottom of the drill stem.

BOD – Biochemical oxygen demand. It is the amount of oxygen required to oxidize the various organic chemicals in wastewater treatment. The oxygen demand can be also defined as chemical oxygen demand (COD), when almost all organics need to be converted into carbon dioxide and water. COD is 1.5 times BOD_5 (see Chapter 6 for details).

Capillary fringe – The zone where groundwater is drawn upward by capillary force.

Carbonate – Sediment formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron.

Carbonate rock – A rock consisting of carbonate minerals, such as limestone and dolomite.

Cations – An ion having a positive charge and, in electrolytes, characteristically moving toward a negative electrode.

Chlorination – The process of adding chlorine to water to kill disease-causing organisms or to act as an oxidizing agent.

Chlorinator – Any device that is used to add chlorine to water.

Chlorine residual – The amount of chlorine present in the distribution system.

Coagulant - A chemical used in water treatment for coagulation. The most common coagulants are aluminum sulfate (alum) and ferric sulfate.

Coagulant aid – A chemical added during coagulation to improve the process by stimulating floc formation or by strengthening the floc so it holds together.

Coagulation – The water treatment process that causes very small suspended particles to attract one another and form large particles.

Coliforms – A group of bacteria, some of them fecal coliforms, normally found in human and animal feces. They grow in the presence of bile salts and ferment lactose-producing acids and gas.

Colloidal particles – Extremely small solid particles that will not settle out of a solution (sizes from 0.0001 to 1 micron).

Contamination – The degradation of water quality from its natural condition as a result of human and animal activities.

Detention time – The average length of time a drop of water or a suspended particle remains in a tank or chamber. Mathematically, it is the volume of water in the tank divided by the flow rate through the tank.

Digestion – The breaking down of organic waste by bacteria.

Disinfection – The water treatment process that kills disease-causing organisms in water. Chlorine is the most common chemical used.

Dissociation - The processes in which water has the natural tendency to break down part of any volume of water spontaneously into hydrogen, (H^+) and hydroxyl (OH^-).

Dissolved solid – Any material that is dissolved in water and can be recovered by evaporating the water after filtering the suspended material.

Drawdown – The distance below the water table that the water table in a well falls to when steady state pumping is in progress. It is the distance between the static water level and the dynamic water level.

Dynamic water level – A water level in a well during steady state pumping.

Effluent – A waste liquid discharge from an industry or municipal treatment process in its natural state or partially or completely treated and discharged into the environment (such as into streams, rivers, lakes, and seas).

Erosion – The general process or group of processes whereby the materials of the earth's crust are moved from one place to another by running water, waves and currents, wind, or glacier ice.

Filtration – The water treatment process involving the removal of suspended matter by passing the water through a porous medium such as sand.

Floc – Collections of smaller particles that have come together into larger particles as a result of coagulation/flocculation processes in water treatment.

Flocculation – The water-treatment process following coagulation that uses gentle stirring to bring suspended particles together so they will form larger particles, or clumps called floc.

Hardness – A property of water that causes an insoluble residue to form when the water is used with soap. It is primarily caused by the presence of calcium and magnesium ions.

Humic/humus – Material resulting from the decay of leaves and other plant matter.

Infiltration – The process in which water is seeping to the ground or entering a sewer system, including sewer service connections, from the ground, or through such means as, but not limited to, defective pipes, pipe joints, connections, or manhole walls.

Ion – An element or compound that has gained or lost an electron, so that it is no longer electrically neutral but carries a charge.

Loading rate – The flow-rate per unit area of a sewage, filter, or ion exchange unit.

Pathogen – A disease-causing organism.

Percolate – The act of water seeping or filtering through the soil without a definite channel.

Pretreatment/Preliminary treatment – Any physical, chemical, or mechanical process used before the main water treatment processes, such as screening, pre-sedimentation, and chemical addition.

Runoff – Precipitated water flowing to streams and rivers.

Saturation – A point at which a solution can no longer dissolve any more of a particular chemical. Precipitation of the chemical will occur beyond saturation point.

Screening – A pretreatment method that uses coarse screens to remove large debris from the water to prevent clogging of pipes or channels to the treatment plant.

Sewage – A waste that includes excreta and other domestic and municipal wastes and industrial effluents.

Static water level – The level of water in a well that is not being affected by withdrawal of groundwater.

Transpiration – The process by which water is absorbed by plants through its roots and evaporated into the atmosphere from the plant surface.

Vadose zone – The zone containing water under pressure less than that of the atmosphere, including soil, water, intermediate vadose water, and capillary water. This zone is limited above the land surface and below by the surface of the zone of saturation (i.e., the water table).

Wastewater – Domestic sewage, industrial effluent, or a combination of these two, as in the case of municipal sewage from industrial areas.

Waterborne disease – A disease caused by a waterborne organism or toxic substance.

Water table – The surface between the vadose zone and the groundwater; that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

Weathering – The in-situ physical disintegration and chemical decomposition of rock materials at or near the earth's surface.

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Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 3002	Subcontract report, April 1, 2001 – Sept. 1, 2001

4. TITLE AND SUBTITLE
Renewable Energy in Water and Wastewater Treatment Applications

5. FUNDING NUMBERS
AAM-1-31224-01

6. AUTHOR(S)
N. Argaw

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/SR-500-30383

11. SUPPLEMENTARY NOTES
NREL Technical Monitor: L. Flowers

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This guidebook will help readers understand where and how renewable energy technologies can be used for water and wastewater treatment applications. It is specifically designed for rural and small urban center water supply and wastewater treatment applications. This guidebook also provides basic information for selecting water resources and for various kinds of commercially available water supply and wastewater treatment technologies and power sources currently in the market.

14. SUBJECT TERMS
renewable energy; water treatment; wastewater treatment

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL