Chapter 2
Drinking Water Treatment Technology—Comparative Analysis

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Abstract Water treatment technologies have evolved over the past few centuries to protect public health from pathogens and chemicals. As more than a billion people on this earth have no access to potable water that is free of pathogens, technologies that are cost effective and suitable for developing countries must be considered. Sustainable operation of these treatment processes taking into consideration locally available materials and ease of maintenance need to be considered. In this chapter, we consider natural filtration for communities of various sizes. In natural filtration, slow-sand filtration and riverbank filtration are considered. Slow-sand filtration is suitable for small to medium size communities, whereas riverbank filtration can be suitable for small to very large communities depending on site and river conditions. Membrane filtration is another technology that can have application to individual households to moderately large communities. Both pressurized and gravity-fed systems are considered. For the developing regions of the world, small membrane systems have most applications. Solar distillation is a low-cost technology for sunny regions of the world. Particularly, it has the most application in tropical and semi-tropical desert regions. It can use low quality brackish water or groundwater for producing potable water. These systems can solely operate with solar energy. The scale of application is for individual households to very small communities. Solar pasteurization, like solar distillation depends on solar energy for purifying small quantities of water for individual or family use. It is most suitable for remote, sunny, high mountain regions such as the Andean mountains, central Africa or the Upper Himalayas where electricity is not available. Also, reliance on firewood is not feasible due to barren landscape in many of these regions. Also, case studies of natural (riverbank and lakebank) filtration, membrane filtration, solar distillation, and solar pasteurization are presented.

Keywords Natural filtration • Solar distillation • UV radiation

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2.1 Introduction

The goal of all water treatment technologies is to remove turbidity as well as chemical and pathogenic contaminants from water sources in the most affordable and expedient manner possible. Many technologies, which have been developed, work best in demand-specific contexts: either the demand of mass-volume or of mass-flow. In all technologies discussed throughout this book, the sun's energy or the soil's filtration capacity or energy efficient membrane filtration are the primary mechanisms of purification. The main components which will be compared in this section include flow rate (m^3/day), cost of implementation, maintainability (which includes cost of maintenance, availability of spare part and materials, and technical knowledge required for repairs), energy consumed (either MJ/h or kW/h), and reliability (as a function of total number of serial components and the sensitivity of each component to long exposure to adverse conditions).

While discussing technology, it will be important to keep in mind the ethic of engineering water systems, acknowledging the social re-shaping which occurs inherently within design implementation. As stated by Priscoli (1998) the answers to water management systems "depend, to a great degree, on what you want or think the ecology ought to be." (Priscoli 1998) He outlines four main views of technological intervention: gigantism, technological triumphalism, historical romanticism, and techno-phobias. The first two reflect mindsets, which hold technology in too high a regard, with gigantism referring to massive infrastructure installation and triumphalism referring to some enigmatic future point where technology becomes superior to nature. The latter two views debase the value of technology and its ability to address water issues around the globe with romanticism quoting partially-factual events and systems in the past and criticizing present uses of technology, and with phobias technology is never a correct answer as it replaces the "natural way" to some degree. Therefore, as each technology is discussed and mentioned throughout this book and as users consider implementation of specific technologies, it will remain important to be aware of ecological and ethical impacts of the technology. The spatial applicability of the technologies varies widely. While some are more appropriate for communities (cities or towns, e.g., natural filtration), others are more appropriate for families or individuals (solar pasteurization, solar distillation).

2.2 Natural Filtration

Perhaps the most ubiquitous of treatment technologies humanity has employed is natural filtration since the beginning of written history. In Exodus 7.24 of the Bible states "And all the Egyptians dug round about the Nile for water to drink, for they could not drink of the water of the Nile." Thus implying the hole on the bank provided clean water relative to the contaminated water of the Nile. Quite simply, natural filtration takes advantage of the soils that act as filters as the water passes through them. It is important to note that there is a difference between drawing groundwater from aquifers and utilizing natural filtration to produce drinking water when the water comes from a surface source. The groundwater in aquifers results from a form of natural filtration of rainwater. There is also riverbank filtration, which is drawing infiltrated river water as it migrates toward pumping wells in adjoining alluvia aquifers, and there is constructed slow-sand filters, which take advantage of the natural filtration attributes of well sorted soils in a constructed—and therefore well contained—environment.

The most common form of natural filtration used currently is sand filtration in a natural setting. However, as more studies are being published on the advantages of true natural filtration, more projects are being undertaken to utilize riverbank filtration. Also, simple wells can be classified as using natural filtration, assuming the soil isn't contaminated and most of the water drawn from the well is a result of rainfall infiltration, but discovering answers to those questions are more technically demanding than this introduction section, and will therefore not be discussed. The focus shall remain on water treatment technologies and not water supply technologies because unless wells are located within a reasonable distance from an open water source, they are too ambiguous as to source and purification attributes.

The best materials to be used for natural filtration are unconsolidated alluvial deposits due to high hydraulic conductivity. The greatest disadvantage of using unconsolidated soil is that there is the possibility of the introduction of anthropogenic contaminants from the land surface to groundwater (typically alluvial aquifers are unconfined aquifers). However, there are clear advantages: natural filtration of appropriate travel time can induce a 3–5 log reduction in microbes and protozoa (Schijven et al. 2002). A 1 log reduction represents a 90% removal of the bacteria or protozoa. Therefore, a 3–5 log reduction removes all unwanted biological and viral components from water to an undetectable—or at the very least, an acceptable—level. However, due to the changing redox conditions, there are often increased amounts of manganese and iron in naturally filtered water, as well as the formation of some sulfurous compounds that are malodorous. These negative effects are eliminated when using rapid sand filtration, but the advantages are also subdued, as will be seen in the section below on sand filtration (Hiscock and Grischek 2002).

2.3 Riverbank Filtration

Surface water in river systems is dynamic: it is flowing downstream, it is evaporating or taken up by riparian vegetation, it is infiltrating into groundwater (or it is entering the river from the groundwater through its bank and bed), and its ability to do all of this is highly impacted by the geologic composition of the immediate environment. There is also a dynamic interaction between surface and groundwaters in natural settings. When the river floods, water from the river gets stored in the soils in the bank areas and the low-lying areas between the floodplains. When the river level drops, the stored water from the bank areas slowly drains back to the river.

Riverbank filtration takes advantage of the infiltration of river water into a well through the riverbed and underlying aquifer material. This is a natural filtration process in which physico-chemical and biological processes play a role in improving the quality of percolating water. After a certain zone of mixing and reducing, the infiltrated water is at its cleanest: almost all river contaminants are removed. Wells are installed in this zone to pump the water to be used for drinking. The purity of this water and its suitability for drinking is outstanding, even in examples where there is an event that introduces a shock load of contamination into the river. Due to the geologic media's ability to remove the contaminants and travel time of water abstracted for natural filtration, the impact of such an event is minimal and requires minimal treatment to address.

The size of riverbank filtration systems vary widely—some systems producing less than 1 million gallons per day to others producing hundreds of millions of gallons per day. The production at a site depends on the utility's need, number of wells at the site, type of wells and pumping capacity of each well, local geohydrology, hydraulic connection between the river and the aquifer, distance and placement of the wells from the river, and a host of other factors. Ray et al. (2002a, b) provides comparative production of water at various RBF sites.

In a natural environment, the variations in production from RBF wells are caused by two main factors: local hydrogeology and river hydrology. While it is critical to consider the hydraulic conductivity of the aquifer, one must also consider the river hydraulics such as grain size of the clogging layer, shear force against the riverbed (to gauge erosion, transportation, and deposition factors for clogging), mean velocity, the hydraulic gradient line, and flood peaks. In addition to local hydrogeology and river hydrology, it is also important to understand catchment zones and other sources of infiltration in the broader geological region affecting the site. The result of these factors combined is a rather tedious and technical scenario, which requires immense amounts of research before being able to confidently draw pure water.

However, riverbank filtration has been used for 130 years in Germany (Schubert 2002a, b) yet it wasn't until the 1980s that any significant amount of research was published beyond the water utilities operating the RBF systems in regards to the parameters mentioned above. Therefore, despite the technical complexities of developing a well-understood site, there are general and basic parameters that can be very simply employed to ensure water quality from riverbank filtration. Three very easily identified parameters are river condition, soil and aquifer composition, and well location.

Due to riverbed clogging (often termed colmation in Europe), it is best to develop riverbank filtration sites in areas where sediment transport is taking place. Also, regions that are experiencing erosion tend to not have as deep alluvial materials to extract the water from, again making regions of sediment transport preferable for developing riverbank filtration systems. This region is common in foothills and valleys and is generally characterized by large bends in the river, and low to moderate flow velocity (0.5–2.5 m/s) depending on sediment load and riverbed composition. As stated previously, the best conditions for riverbank filtration are in unconsolidated alluvial deposits (although there are examples of low-permeability zones being used for natural filtration (Ray et al. 2002b; Hubbs 2006). Wells used in the alluvial aquifers have used a variety of technologies for installation. For example, vertical wells or horizontal collector wells used in western countries use mechanical means for drilling and installing laterals (screens). While modern technologies are being used in India currently for the installation of new vertical or horizontal collector wells, many operating large collector wells (e.g., those at Hardwar, India) were built manually by digging the soil and making the caisson and installing the gravel and cobble pack around the port openings. Most Indian companies still use direct push technology for installing laterals in which the screen pipes with open holes are pushed directly into the aquifer.

Groundwater pumped very near a surface water source may contain contaminants found within the open water source. However, groundwater pumped at a long distance from an open water source can be affected by contaminants that are typically present in groundwater. Therefore, there is an identified "mixing zone" associated with each surface water source. This zone is defined as the zone where contaminants from surface water have been removed without the addition of groundwater contaminants. Zone width is a function of hydraulic conductivity, and is dependent on mean travel time, with targets between 5 and 20 days. Therefore, it can be reasonably attributed that on the scale of technologies being compared in this book, riverbank filtration does not demand excessive technological expertise to develop or maintain, particularly in regions without any access to any form of filtered or cleaned water source.

Use of multiple wells and redundancy are some of the common ways to ensure steady supply of water during repair and maintenance of wells or during mechanical failures of pumps or well rehabilitation. Multiple wells constitute a parallel process where one or more wells can be off line and the system can still meet demand. However, simply because there are so many individual wells involved introduces the chance of failure and therefore maintainability becomes a larger issue, particularly for regions without access to surplus manpower or materials for repair. When multiple vertical wells are used in riverbank filtration systems, the pumping efficiency can be increased by installing a siphon system and pumping the water from the caisson where the siphons empty the water from multiple vertical wells. Such a system is operated at Düsseldorf, Germany.

Due to the use of large mechanical pumps, riverbank filtration relies on either an electrical power grid or internal combustion engines to provide enough energy to the system for operation. There is also a dependency on larger infrastructure as many sites utilize multiple wells, and must therefore be connected to a common storage point or multiple storage points. Either way, the system-wide maintenance demand is larger than what is required for slow sand filtration (another natural filtration system), but less than the requirements for membrane filtration based on the size of the compared systems. Since the only distillation and pasteurization discussed in this book are solar-powered technologies, it is difficult to compare the energy consumption of a system that could be solar but may also very likely be diesel or electrical-grid. However, even if PV panels were used to supplement energy needs, the area of panels required to power well pumps can sometimes exceed practicality depending on well depth, hydraulic conductivity, and topographic/weather allowances for PV arrays, along with human/livestock complications of installing a relatively large solar array. Therefore, it is not unreasonable to assume that riverbank filtration will depend on a pre-existing electrical grid or diesel/biofuel/hybrid generators. Since this is the only technology that inescapably requires pumping (while some others may need it only in certain conditions), riverbank filtration requires more absolute energy than most other technologies considered. This, however, does not include delivery systems, which may often require additional pumps, or appropriately scaled pumps to handle both withdrawal and distribution. Therefore, the total combined energy required for any system will also be a function of the service area of that system.

Use of large pumps is one of the key considerations in riverbank filtration systems. Newer systems use variable drive pumps that require cool (air conditioned) environments to operate. Other technologies, with the exception of various membrane filtration technologies such as reverse osmosis (RO) do not have need for pumps. Sand filtration or solar distillation has low energy. Also, unlike solar energy dependent technologies, riverbank filtration would have dependable supplies due to the use of electric or diesel motors.

Conversely, compared to other forms of water treatment technologies for large systems, riverbank filtration is one of the easiest to implement due to relatively low technology demands and simplicity of construction, training, and operation. In this, it is meant that the concept of drawing water from the ground is as old as history, and therefore justifying digging wells near a river is quite easily done. Convincing locals that water from the well is more pure than river water may require some work, since the work of purification by soil is not easily observed by users. Riverbank filtration also has the capacity to begin at a smaller scale to demonstrate the purity of water drawn and later expanded into a larger scale due to its parallel nature. In fact, many utilities operate a pilot well a year before building a full-scale system.

Manpower to dig wells is available around the globe. Pumps of various levels of technology can be found in almost as many places as Coca-Cola®, and the training required to understand how to use a pump/well system is almost minimal due to their pervasive use. This allows a technology to be introduced that minimally alters expectations, can be easily understood, can be scalable, and can have tangible, observable results. The combination of these attributes makes riverbank filtration an attractive option to introduce to regions with access to contaminated surface water, but little or no access to purified water.

Potentially one of the challenges facing riverbank filtration is water-rights mitigation and legal intricacies. This only affects regions with water-rights policies (e.g., western United States), but increasingly more of the world is affected. However, many riverbank filtration systems are successfully operating in the Western United States. Therefore, it is important to consider the potential legal ramifications of implementing a system that removes water from a broader, underground source.

2.4 Slow Sand Filtration

Slow sand filtration is a fabricated form of natural filtration, which is created within a man-made context for the specific purpose of filtering water. This filtration method has been municipally used since the nineteenth century, and continues to be an excellent filtration method. As stated by the World Health Organization's Water Sanitation and Health (WHO WASH) division in their 1974 report *Slow Sand Filtration*, "Under suitable circumstances, slow sand filtration may be not only the cheapest and simplest but also the most efficient method of water treatment" (Huisman and Wood 1974).

Constructed from simple materials such as wood or even a modified shipping container, slow sand filters are basic enough to be adaptable to a wide range of available materials. The filter itself is usually 1 m thick, with a minimum of 0.7 m of fine sand. The remaining portion that isn't sand is gravel and pebbles located at the bottom of the filter to allow the purified water to collect and drain from the container. The filter is then filled with water until saturated, and there must also be supernatant water on top of the sand in order to cultivate and sustain the *Schmutzdecke*. There are no mechanical components, and no electricity is required to operate. Gravity is the external force, and the natural bacteria and protozoa within the *Schmutzdecke* actively treats the water.

It is, in fact, the *Schmutzdecke* that is responsible for nearly all the filtration that happens. Quite literally, it means "grime or filth" in German, as it is a small biofilm which forms at the sand-supernatant boundary consisting of naturally occurring bacteria and other organic compounds, which interact with the water as it passes through. It is this interaction that is able to filter out particles smaller than the inter-granular space created by the sand and other biodegradable contaminants; and therefore it is much more efficient at purifying water than rapid sand filtration.

Rapid sand filtration is simply a slow sand filter without the *Schmutzdecke* (or biofilm) and is typically employed at a majority of water filtration plants. Therefore, the only filtration that occurs is due to the sand particles hindering large suspended colloidals from passing through the intra-granular space and to some physico-chemical interactions between the sand and the contaminants. It cannot purify water nearly to the degree slow sand filtration and riverbank filtration can, and for its efficiency it requires frequent backwashing. Backwashing is an engineering challenge for systems that operate on low technology. Often other processes such as coagulation, flocculation, and sedimentation are employed before engineered filtration using rapid sand filters. Thus, it is not considered a "natural" filtration system.

Cleaning of slow sand filters takes place between once every three weeks and once a year, depending on the quality of the raw water source. It is also well within grasp of an ordinary citizen, though knowledge of how the process is actually cleaning the filter is helpful. Additionally, in order for a slow sand filter to be fully operational, it requires 1–2 days for the biofilm to form, and until then the filtered water is not usually suitable for drinking, and must therefore be recycled through the filter until a full biofilm is in place. Then, the biofilm continues to grow throughout the use of the filter and must therefore occasionally be cleaned. When the biofilm becomes too thick, it begins to impede the flow rate of the filter, and when head loss has reached the design flow maximum, the filter must be cleaned. While there are several methods used to clean slow sand filters, only one will be mentioned now. Referred to as "mechanical scraping" the name can be misleading unless the scraper is automated. In remote locations, the filter can be cleaned by draining the water, drying the sand, and scraping the *Schmutzdecke* off the top layer via manual labor. Then, with a fresh surface of sand for a new biofilm to grow upon, water can be reapplied with the necessary 1–2 days growth period required.

The drawback of sand filters is their inability to fully treat highly turbid water. It is quoted that water with a turbidity of 10 NTU or higher cannot be adequately treated by sand filtration, and water with turbidity enhances the life of the filter and reduces clogging (Tech Brief: Slow Sand Filtration 2000). In order to reduce the turbidity of water, settling tanks may be utilized or even developing several pre-filtration sand-sieves to remove larger particles or aggregates. Due to utilizing the ecological interactions of living bacterium, slow sand filters are not ideal for year-round use in cold climates when the bacteria may become dormant in winter months. In such situations membrane filtration or solar purification may be more appropriate.

An additional drawback lies within the name of this purification method, as it is indeed a slow filter. Flow from a slow sand filter range from 0.015 to 0.15 m^3/m^2h, which can be as much as an order of magnitude lower than other technologies' per unit area output. Thus, for large cities, large filter beds are needed. Storage is also required to mitigate peak demand, and therefore maintaining the purity of the stored water is an introduced maintenance factor.

However, due to their simplicity and size, slow sand filters also have several advantages. Technologically speaking, they are the simplest technology considered, which aids in minimizing maintenance and expediting the education of the community users. Also, due to the fact that the entire system can be very easily self-contained, sand filters are easily scalable. Implementing a sand filter with a surface area of 1 m^2 would not be complicated by expanding to a 10 m^2 basin as long as there is a minimum of 0.7 m of fine sand, and time is given for the biofilm to form.

Material access to sand, gravel, and materials to construct the basin within is widespread, with perhaps the caveat of the drainage plumbing. Additionally, the financial cost associated with the materials, installation, and maintenance is significantly lower than anything else mentioned in this paper. Such an inexpensive project is easily funded by non-profit or microfinance organizations. Additionally, due to the low cost of sand, the installation cost per square meter decreased rapidly with an increase in filter area.

Some studies have concluded that slow sand filtration requires a large footprint (Huisman and Wood 1974). While slow sand filtration is quite practical for large scale applications, it is perhaps even more practical among individual and small community users. Under small-volume demand, the footprint needed for slow sand filtration reduces considerably. While some municipal plants have 200 m^2 of filter area, some home use as small as 10 m^2 (Tech Brief: Slow Sand Filtration 2000). And while riverbank filtration utilizes space underground, and therefore could be argued to use less space, if the region has water-rights laws in place, the size of land area for riverbank filtration becomes quite a serious consideration.

Interestingly, some studies have come to contradictory results. In the Nainital region of northern India (see case study below), it was found that rapid sand filtration was sub-par compared to natural filtration, as it did not remove nearly enough coliform or COD to meet national standards (Dash et al. 2008). However, in a study done by the University of New Hampshire (2003) of five locations in the eastern United States it was found that slow sand filtration was more successful at removing coliform and *E. coli* than natural filtration. It was found, however, that natural filtration was superior in removing dissolved organic compounds (DOC) (41–85% as opposed to 8–20% for sand filtration) and total organic compounds (TOC) (55–75% as opposed to <30%) (Partinoudi et al. 2003). Therefore, it can be generally concluded that when using slow sand filtration (and not fast sand filtration), it is better in an environment that is dominated by protozoa as opposed to a system that has high levels of other organic compounds.

By way of comparing the differences between riverbank filtration and slow sand filtration, the United States Environmental Protection Agency (US EPA) has developed "purification credits" for both technologies as a gauge of how well they meet US EPA drinking water standards. Slow sand filtration is given a log-reduction credit of 3-log removal for *Cryptosporidium* (Ray et al. 2002b). The US EPA requires a 2-log removal for *Cryptosporidium*, and even under the new Long Term 2 Enhanced Surface Water Treatment Rule (which increases the required log reduction by 1–2.5 log), therefore RBF should be used as a "pre-filtration" technology aimed at reducing the load placed on slow sand filters or other filtration devices.

As was stated by the World Health Organization (Huisman and Wood 1974), and reaffirmed through this brief analysis, slow sand filtration is an attractive purification method for situations where low technology and low cost are required, but high quality output is demanded. Its drawbacks are the slow rate of filtration and the inability to purify water with high turbidity; notwithstanding, slow sand filtration is a technology worth considering in virtually any project scenario. We have limited our discussion to riverbank filtration as the sole natural filtration in this book.

2.5 Membrane Filtration

Membrane filtration technology is simply the filtering of water through a sieve or semi-permeable layer such that water molecules are allowed to pass through, but bacteria, chemicals, and viruses are prevented from passing. The sophistication of membrane technology ranges from using a sand-filled T-shirt fed by gravity to highly advanced pressurized systems relying on nano-technology to actively screen microbes.

2.5.1 Pressurized Systems

The most effective membrane technology, pressurized systems, often require significantly more energy than other membrane systems due to electrical or mechanical systems required to maintain the pressure in the system. Yet because of the pressure introduced to the system, the pore spaces in the membrane can be significantly smaller, allowing higher removal rates of contaminants. The most common application of membrane technology is in RO desalination although the application of membrane technology has been used for bacterial and protozoan removal as well. Other desalination processes are membrane filtration (nanofiltration [NF], ultrafiltration [UF], and microfiltration [MF]) and electrodialysis (ED). All three membrane filtration systems are pressurized membrane systems primarily used to purify seawater or brackish water (water containing less salt that seawater, but still more salty than WHO regulations).

Reverse osmosis is used to take saline water and convert it into pure water. It currently makes up 80% of desalination plants for a cumulative 44% of all desalinated water volume (Greenlee et al. 2009). The technical measure of fresh water is to contain less than 1,000 mg/l of salts or total dissolved solids (TDS) and the World Health Organization has established a baseline of 250 mg/l, which is also supported by the US EPA (LT2ESWTR 2006). Therefore, any water containing higher levels of salts or TDS must undergo some sort of removal process.

The energy required for RO is significant due to the nature of the membrane surface (Fig. 2.1). Since RO membranes are considered non-porous, diffusion is the primary transportation function for water to pass from high concentration to low concentration. As stated in Table 4.3 (chapter on desalination) seawater RO requires approximately 3–6.5 kWh/m^3 to reduce average salinity (36,000 mg/l) to below drinking water standards (800 mg/l). While this is significantly less than other desalination technologies discussed in Chap. 4, it is also higher than other technologies compared in this section. As an example, according to Srinivasan (1993), the

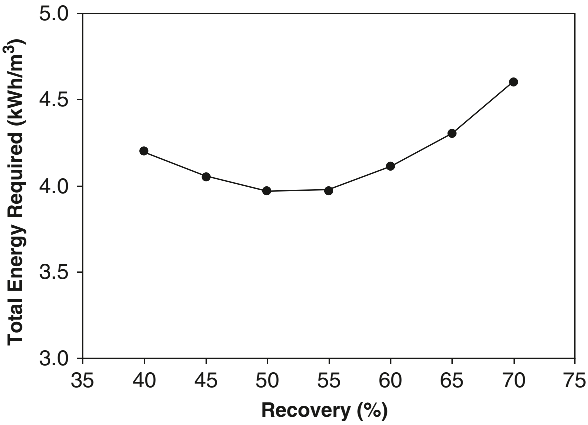

Fig. 2.1 Total energy required per volume of permeate as a function of RO system recovery. (Source: Greenlee et al. 2009)

average solar energy in India is 5 $kWh/m^2/day$ and therefore RO would only be available in certain more sunny regions of India if PV were to provide the energy source.

Since the energy is proportional to the membrane permeability and the feed pressure, the specific kWh/m^3 energy consumption is determined by the feed water make-up, drinking water standards, and flow criteria. Another large component is the recovery rate the RO system is designed to operate under. The trade-off with recovery rate is that a higher rate usually means more saline passage through the membrane, but results in higher outflow.

The cost of membrane desalination is dependent on location (water quality, geography, local economy, etc.) and volume (of required treated water). Greenlee et al. (2009) reported that large RO desalination plants (3,500–320,000 m^3/day) have a cost between \$ 0.53 and 1.94/m^3 where as small plants of 0.1–1.0 m^3/day have costs between \$ 30 and 36/m^3. However, much of the high cost of small RO plants is due to research instrumentation, which would not be present in on-site installations. Estimates say 40% of the cost will be reduced when implemented in the field.

The pressure required for RO to occur is significant. First, natural osmotic pressure must be overcome by increasing the hydrostatic pressure of the system. For seawater, the osmotic pressure ranges between 2,300 and 3,500 kPa. To overcome this, many RO plants utilize between 6,000 and 8,000 kPa of pressure.

A turbidity of less than 0.2 NTU is recommended for RO systems as fouling occurs at higher rates. The capacity for a membrane to be fouled is exponentially related to the amount of particulates in the feed water. This demonstrates that RO is much more sensitive to particulate than slow sand filtration, requiring higher levels of pretreatment.

The overwhelming majority of technical papers and research articles produced on membrane filtration focus solely on desalination. However, the use of membrane filtration for pretreatment of RO plants is becoming more common. This is no different than simply using the same pretreatment technology to purify water that has no salt concentration for drinking. Pretreatment for RO can utilize various options, but of most interest to this section is the use of MF, UF, and NF. The differentiation between each is the pore size of the membranes (as they are considered porous, unlike RO membranes), with MF being the largest pore-size and NF being the smallest. The ability of each to filter out contaminants is beneficial in various environments, and the correct application of membrane pore-size is largely dependent on the most common contaminants in the feed water.

UF has surfaced as the most common choice for RO pretreatment as it balances the screening capacity of nanofiltration with the flux capacity of MF. NF is primarily used for brackish water and dissolved organic compounds. This is a unique divergence beginning from the classic use of membrane technology, as it represents a more standard water treatment technology as it moves away from strict salt-removal uses.

Another treatment technology used for brackish or salt water is distillation. Distillation can also use a membrane, such as membrane distillation (MD), which utilizes membrane pore-sizes similar to MF, UF, and NF to purify water. The principle of MD is to create a temperature gradient between the feed and permeate sides of the membrane, so water is pulled through on the basis of liquid-vapor equilibrium. This is achieved by using the vapor pressure as the mechanism that moves water from one side to the other. The advantages of MD are that it requires less pressure than RO and less heat than multi-stage flash (MSF) distillation or multi-effect distillation (MED) technologies. Additionally, it can be used in a wider range of applications (such as sustainable water treatment), and can be easily combined with renewable energy sources such as PV panels or wind generated energy (Al-Obaidani et al. 2008).

The cost of MD is quoted to be \$ 1.17/m^3 for a hypothetical plant producing 24,000 m^3/day. However, in conjunction with solar power and a heat recovery system, the price per cubic meter drops to \$ 0.56/m^3, which is similar to that of RO (Al-Obaidani et al. 2008). The same challenge that faces RO would also face MD: as production size is reduced, the cost per cubic meter increases significantly. Karagiannis and Soldatos (2008) report that for plants producing between 2 and 3 m^3/day the cost of seawater desalination is between \$ 3.40 and 6.90/m^3. For communities outside the reach of metropolitan infrastructure and without a sufficient population to justify large plants (or the volume of source water to feed such large plants), it is necessary and practical to create small-scale plants. Additionally, through the development of sustainable components and creative local design, the cost of water would continue to fall. It is good to keep in mind that the volume of permeate water is orders of magnitude less on small systems than on large and as such the aggregate cost is significantly less. For a large volume plant, daily operation costs are between \$ 25,000 and 50,000/day, whereas for small volume plants daily costs are around \$ 25–50/day, significantly less cost for the community, even though the per cubic meter cost is higher.

2.5.2 Gravity-Fed Systems

Gravity-fed systems are almost too simple to be worth mentioning, but it is good to be familiar with them since sometimes they are sufficient to purify local water sources. Most often, these systems are used in conjunction with slow sand filtration where the membrane is the medium used to support the sand. Often, large-pore membranes such as cloth fabric or canvas are used. Clearly gravity-fed systems are not designed for high-concentrations of contaminants, but rather to be used as a cheap pre-filter of large suspended colloidal matter in source water.

The cost of gravity-fed systems is so low that it is rarely recorded. Often, the components which make up the system are collected from what the community has on-hand or are purchased at a common convenience store by someone visiting a local city, and are therefore significantly below the scale of costs discussed in this book. The sophistication and corresponding cost of gravity-fed membrane filtration compared to other technologies discussed is similar to attempting to compare a child's lemonade stand with a MinuteMaid® factory. However, it deserves consideration, because if a community discovered that large suspended solids are the primary contaminant, gravity systems may be sufficient to meet their needs. There is often excitement about the implementation of some new technology because of its advanced design and capacity beyond what is expected, but sometimes this excitements leads to overspending beyond what the community has the capacity to support. Therefore, the cheapest options are sometimes the best, even if re-visiting the site several years in the future is a necessary part of implementation.

2.6 Solar Distillation

Before beginning a discussion on water treatment systems that utilize solar power, it is worth mentioning the sun and how much power is actually available. As the Earth is an imperceptible cosmic dot from the sun's perspective, very little of the total energy emitted from the sun ever reaches the Earth. In fact, at the outmost reaches of our atmosphere we receive only one-billionth of the energy that the sun produces. The sun's energy per unit area is called solar flux, and is generally measured in W/m^2. While the extraterrestrial solar flux (flux at the outer edge of our atmosphere) is 1,353 W/m^2, this can never be reached on the Earth's surface. If the solar flux were that high on the Earth's surface we would be in much greater danger from the sun, so we are quite thankful that the atmosphere absorbs much of the solar flux. However, the interference from the atmosphere complicates solar technologies. Due to atmospheric diffusion, solar flux is reduced by at least 15–30%, even on the sunniest day of summer on the equator. Typically, solar flux from 300 to 1,000 W/m^2 is referenced as being used for solar technologies. Often times, references to higher solar flux values include the magnifying characteristics of compounding reflectors.

Solar technology is surprisingly fickle as it is heavily dependent on sufficient solar flux. Attributes that affect solar flux are absorption and scattering by the atmosphere, the time (day, month, or year), latitude, altitude, and meteorological effects. Additionally, technology used to capture the sun's energy is expensive to manufacture and produce, though often not as expensive as other water treatment technology costs.

Under current systems and operations, desalination costs are substantial for developing communities—particularly those with comparatively small populations. The infrastructure required to produce and support continuous desalination and purification—including power supply, pre-treatment, brine management, janitorial maintainability, repairs and modifications maintainability, and inventory—is a daunting task when the protective hedge of other city-sized systems are far removed. However, while cities may have the cash flow to employ full-scale operations to alleviate water needs, those left beyond the reach of urbanization have hand-collected water from unsanitized sources as their only recourse. Yet despite developing countries with 50–70% of their population living in the few urban centers (UN DESA 2007), there still remains hundreds of millions of people qualified by the UN as being "water-stressed" who need access to cheaper and more reliable technology to bring them clean water.

Solar distillation is a rising star among such technologies. A very simple technology in both concept and design, solar distillation utilizes the natural process of evaporation to capture purified water. The structure used in solar distillation is called a solar still, and a common solar still has a slanted glass cover over a black-painted, water filled basin. As sunlight penetrates the device, solar energy is absorbed by the basin liner and transferred to the water via conduction and convection. Minor heat losses exists from reflection by the glass and water surface, and absorption from the basin liner (energy is transmitted to the ground).

As the water evaporates, water vapor begins collecting on the glass cover. As build-up occurs and condensate beads become larger, gravity overpowers adhesion and the purified water molecules trickle down the slanted glass plate to collect in a gutter designed to capture the pure water and carry it to a storage tank or spigot. Since evaporation is the mechanism of purification, this technology is effective for the complete removal of all chemical, organic, and biological contaminants within the feed water.

However, solar distillation requires higher amounts of solar energy for longer periods of time than does solar pasteurization or even indirect distillation or UV irradiation. Therefore, solar distillation requires the most amount of solar energy compared to the other solar technologies. While the per-volume demand of solar energy may be higher for UV irradiation due to the utilization of photo-voltaic (PV) panels, solar energy captured when the system is not in use can be stored in batteries to supplement the device at a later time, allowing UV irradiation to operate under lower solar flux scenarios than solar distillation.

Additionally, due to the slow rate of evaporation that occurs even on the most ideal day, the production per square meter of the still is low. Because the still is glass covered and tends to be rather large, the capital cost for implementation can be quite high (for manufacturing the glass and delivering it to the site), and the risk of environmental damage is also significant (from animals, weather, and other unforeseen events).

Since there are no moving parts and the only input required is the addition of more water, maintainability of a solar still is extremely simple compared to technologies such as RO, MD, and RBF. Depending on specific construction, slow sand filtration and solar pasteurization may also have similarly low maintenance requirements. In fact, the only maintenance required is to occasionally clean out the basin of contaminants and the removal of algal growth that builds up over time. This is most common when purifying salt water using solar distillation, though cleaning would still be required if contaminated water had only bacteria and protozoa as the dead microbes would eventually form a layer which would begin interfering with the efficiency of the basin.

Solar distillation is a technology that may be readily accepted in rural areas due to its simplicity and smaller scale of operation. Understanding the concept of evaporation and condensation can be easily grasped by anyone, and small, low yield examples can be delivered to villages. As the community witnesses the cupful of pure water produced each day, it will be understandable for there to be a general desire for larger stills to produce more pure water. Perhaps most advantageous in this regard would be to use solar distillation as an entry point to getting wider local acceptance of technologies such as membrane distillation and solar pasteurization which are harder to observe, but produce more water per unit area.

2.7 Solar Pasteurization

Pasteurization is a concept that has been widely accepted for a substantial amount of time for use in purifying milk and other products, but is only recently coming of interest for water treatment. While some health education efforts in the past have encouraged users to boil water to ensure purity, most protozoa and bacteria are inactivated at much lower temperatures. In the table below (also found in Chap. 3) the temperature required to kill contaminants in a given time is shown. The D-value represents the time required to inactivate 90% of the given contaminant, and a value of 5D represents inactivation of 99,999% of microbes or contaminants.

Temperature	Result
55°C (131°F)	Worms, protozoa cysts D value = ~1 min
60°C (140°F)	*E. coli,* rotavirus, *Salmonella typhi*, *Vibrio cholerae*, *Shigella* sp. D value = ~1 min
65°C (149°F)	Hepatitis A virus D value = ~1 min

It could be suggested that the rule-of-thumb of boiling water has been given to provide users with a visual metric of ensuring that water has been sufficiently heated, but the additional energy required to bring water to a boil (past the pasteurization temperature) is excessive, particularly for environments where access to fuel is limited. Alternative methods of ensuring that feed water is adequately heated (but not boiled) are mentioned in the chapter on solar pasteurization.

Understanding the temperature range of solar pasteurization technology, it becomes quite simple to explain the purpose of the technology: to heat water to the pasteurization temperature (often taken as 65°C) and no higher to minimize the required energy input. The mechanism used to bring water to this temperature varies and will be briefly mentioned in the following paragraphs.

Regardless of the configuration of solar pasteurization and the metric used to determine when pasteurization temperatures have been reached, this technology uses less energy than any other solar technology mentioned. Other than gravity fed membrane systems and slow sand filtration systems, solar pasteurization systems consumes the least amount of energy per volume output of technologies considered. However, similar to solar distillation and slow sand filtration, the volume purified per unit area is quite low, on the order of magnitude of 0.1 m^3/m^2 as further discussed in the chapter on this topic. However, Duff and Hodgson (1999) found that their systems could produce 100 l/day with a flat panel collector with an area of 0.33 m^2 resulting in a nominal production rate of 0.3 m^3/m^2/day.

2.7.1 Flat Panel Collectors

Practically speaking, flat panel collectors work and look similar to photovoltaic collectors. As with many of the developed sustainable solar technologies, the name declares the function. Water is moved through a flat and often rectangular structure, such that sunlight passes through one transparent side and heats up the water to the pasteurization temperature. The design is such that the ratio between surface area and volume is maximized, therefore, the water in the basin is often shallow.

Surprisingly, these panels are excessively prone to the sun's radiation, and therefore have the capacity to purify water at a higher rate than several other technologies mentioned. The average rate of purification for flat panel collectors is 0.17 m^3/m^2/day, and because of this flat panel collectors are convenient to use in regions with high sunlight.

In fact, by using a heat exchanger built in to the flat panel, Stevens et al. (1998) found an increased flow-rate. In his report, Stevens calculates flow on a per hour basis, referencing 10–55 l/h m^2, which would be 0.24–1.32 m^3/m^2/day, assuming a 24 h solar day. Since pasteurization happens for about 6 h a day, the figure becomes 0.04–0.33 m^3/m^2/solar day which is still potentially higher than most other solar technologies discussed which usually hover around 0.1–0.15 m^3/m^2/day.

One major drawback is that large, flat sheets of material are needed for this system to operate properly. The risk developed by the implementation of large-area, exposed components is significant. Complications from the weather, wildlife, cattle, children, and other variables are significant for this technology. Flat panel collectors have a threat from human damage due to playing or climbing on it or accidentally hitting it with other objects. Particularly if there is an integrated heat exchanger, these non-designed human interactions can have a significant negative impact on the performance of the device. Therefore, the flat panels would require some fencing or security to prevent un-intentional uses.

Fortunately, however, there is a low level of technical knowledge required for this technology, making it easy to operate and easy to train users in operation. Since the primary active components of the system are flat-black absorbent paint and glazing to trap solar radiation, the frame and casing can be constructed of a wide variety of materials locally available to the people. This also helps mitigate the amount of technical knowledge required for construction. Since there are no moving parts, maintenance is quite low, and the only expensive component that may need to be replaced is the glazing over the top of the device. However, this is an expensive component and can be difficult to maneuver to the project site safely.

Unless the device is constructed such that a thermostatic valve is in place or some other mechanical/electrical system exists to ensure water is pasteurized before flowing through the system, the technology would have to be monitored intensively during the hours prior to solar noon when the water is being heated, and after solar noon when the solar flux capacity is dwindling so that water stops flowing when it is no longer hot enough to be pasteurized. This calls for one level of complexity beyond the simple flat panel collector, but is necessary to ensure that water is pasteurized. Since it is a flow-through device, an indicator like the WAPI (SCI 2009) used in solar cookers would be insufficient.

2.7.2 Compound Parabolic Collectors

The technical transition between a flat panel collector and a compound parabolic collector is simple: just imagine holding a piece of paper flat in your hand and folding it into a parabolic shape. Many materials used as reflectors have the capacity to be gently folded without rupturing, and therefore much floor space can be saved by utilizing a parabolic collector. Additionally, higher concentration ratio leads to less square footage and materials required for same production compared to flat panel collectors. Since the concentration ratio is higher, water tends to be pasteurized faster, though in a smaller volume, so that the total production for each solar day remains relatively the same.

Due to the deployable nature of the shape, a wide variety of materials can be used. This is advantageous in seeking locally available resources to use as reflectors. Often cardboard covered in aluminum foil is sufficient in this application, again due to higher concentration ratios. Since there is a small volume of water in the device at any given time, the structure typically weighs less than other technologies discussed, and therefore does not demand such a robust frame, which also lends itself to a wider range of creative design with local materials. Also, as water flows through a tube instead of across a large flat area, the risks imposed by external factors are minimized in comparison to flat panel collectors.

The greatest drawback to this technology is two-fold. First, for high efficiency, parabolic collectors rely on double-walled vacuum tubing, which must be manufactured, and therefore imported. This is a major drawback when considering how locally friendly all other components are for this technology. Second, since it is a flow-through device, it is also difficult to ensure that water was sufficiently heated while passing through the device without advanced temperature monitoring systems. Several solutions have been developed to overcome this obstacle, as outlined in Chap. 3.

One method to determine pasteurization temperatures of effluent water is to use a thermostatic valve from an automobile. This is advantageous for communities that have vehicles and therefore would have access to spare parts. However, as a community becomes more remote, it would become increasingly difficult to find spare parts to repair the valve were it to be damaged. Another method that is being used is to create a disparity in the hydraulic gradient line, such that water of insufficient temperature (and therefore insufficient density) could not overcome the vertical barrier. However, once water was heated to the desired pasteurization temperature, it would expand enough due to a change in density to spill over the barrier and into the storage container. This also presents challenges, as the vertical height of the barrier (most commonly a length of vertical tubing) must be precisely calculated based on the physical properties of water. Therefore, if the tubes were to be damaged it would require a high level of technical competence to reconstruct the design, or it would require a location of safekeeping for the original design plans. Heat exchangers can also be used in parabolic collectors after pasteurized water passes through some temperature check valve.

The most expensive component of this technology is either the temperature valve check or the vacuum tubing, depending on initial design criteria. That said, the cumulative cost of this design is relatively cheaper than all other technologies, except for slow sand filtration. This is particularly true if the design allows for local materials to be used for the reflectors. Parabolic compound collectors are a cheap and efficient technology if solar pasteurization is viable for a given community.

2.7.3 UV Irradiation

Irradiation again takes what has been publicly taught on water treatment and moves a step beyond. In the same way that solar pasteurization doesn't require boiling for water to be purified, UV irradiation does not require heat input for water treatment. Instead this technology relies on applying light at specific wavelengths to contaminated water to deactivate bacteria and protozoa. This process has been found to be highly effective and inexpensive while producing a reasonable volume of water per unit area UV light source. There are two mechanisms used in UV irradiation (or solar disinfection). One is referred to as "direct disinfection" and utilizes the sun's natural wavelengths during sunshine hours to disinfect contaminated water. The other, "indirect disinfection," harnesses the sun's energy via PV panels, and applies very specific wavelengths to contaminated water under UV lamps. Since direct irradiation can be coupled with solar pasteurization as the sun will be heating the water even as it is applying neutralizing wavelengths to the microbes, only indirect disinfection will be discussed here as a unique technology. The most commonly accepted UV wavelength used in disinfection is 254 nm, which comprises only 5% of the total wavelengths emitted by the sun. Therefore, it is much more efficient to develop fabricated UV environments which narrow the UV spectrum to emit only that which is ideal for disinfection (Kim et al. 2008).

Indirect irradiation utilizes various lamps to accomplish its goal of deactivation depending on scope and variety of microbes involved. The common classification of UV lamps is low-pressure monochromatic lamps, medium-pressure polychromatic lamps (with both visible and UV wavelengths) and recently there has been the introduction of pulsed UV lamps (Bohrerova et al. 2008).

First to discuss is some basic knowledge of which wavelengths deactivate microbes and how. In the ultraviolet (UV) range, there exists three sub-groups: UVA, UVB, and UVC, and are differentiated by wavelength, with UVA being the longest wavelengths (320–400 nm) and UVC being the shortest (100–280 nm). Each bacteria and protozoa is most sensitive to specific wavelengths, therefore it is usually preferable to have some variance in the spectrum of emitted wavelengths, though systems can be tailored easily to common contaminants to save on energy consumption and inventory variance. Low-pressure lamps are optimized at 253.7 nm, as this wavelength has been determined to be optimal for the inactivation of the widest range of microbes (Bohrerova et al. 2008). Medium pressure lamps and pulse-lamps have an acceptable range between 200 and 300 nm, but additionally medium pressure lamps have "long-pass" frequencies, which include the visible spectrum. Therefore, low-pressure lamps are often categorized as using UVB irradiation, medium pressure lamps tend to be classified as UVA, and pulse-lamps are UVC. In the same way that medium pressure lamps have "long-pass" frequencies, pulse-lamps have a shorter wavelength frequency, as low as 100 nm.

The energy required to operate the lamps varies significantly by project, manufacturer, wavelength specificity, turbidity, and purified water production flow rates. In a direct comparison experiment performed by Bohrerova et al. (2008), the energy required to purify water having *E. coli* concentrations of 1×10^8 cells/ml was given. For low pressure lamps and medium pressure lamps, four 15 W lamps and one 1 kW lamp was used, respectively, while pulse-lamp used had an average power output of 2.5 kW. Each pulse lasted only milliseconds, but was triggered every 10 sec. It was found that the continuous wave lamps (low pressure and medium pressure) required 2 sec–2 min to purify water, whereas the pulse lamp required 1–20 pulses to achieve purification (Bohrerova et al. 2008).

It has been found that solar disinfection is an effective technology in the removal of all biological microorganisms and protozoa, with log reductions ranging between 1.05 and 4.26 depending on the average wavelength of light used (Bohrerova 2008). However, it was also found in a different study (Tranvik and Bertilsson 2001) that the effect of irradiation was dependent on the chlorophyll levels in biologic matter in the water samples, with photobleached organic matter having virtually no response to UV irradiation, but organic matter with some coloration responding favorably to UV irradiation.

One of the disadvantages of solar disinfection is the lack of *observability* associated with this technology. Due to the risk of environmental damage to the lamps (weather, livestock, or human interference), often times lamps must be somehow enclosed. Even still, were the process to be observed it is difficult to visually see the treatment process. This phenomenon of wavelength neutralization is much more technically advanced than other theoretical concepts involved in other technologies, and therefore educating users on how and why UV irradiation works will be a more difficult challenge. Because of this technological gap in knowledge, and because it cannot be intuitively deduced that purification happens when non-visible wavelengths are passed through contaminated water, it will be more difficult for UV irradiation to be accepted by communities as a functional technology. More than the other technologies discussed, UV irradiation can come across as a "black box" technology—contaminants go in one side and come out the other side pure, and there is little understood as to why. While this technology has been used in places like Korea and Japan, for many parts of the world such a technology would require significant explanation.

Therefore, while UV irradiation may be on par with the energy per unit output and the area per unit volume requirements of other technologies discussed, it may be a late-adoption technology simply because of the more advanced technical knowledge required to understand the system. Maintenance knowledge is quite low as changing a light bulb is the primary maintenance requirement, but knowing why a specific type (wattage, wavelength, etc.) of light bulb needs to be there requires significant understanding. For those without a true knowledge of the workings of UV irradiation, it may be falsely assumed that a bulb that produces a lot of light purifies water the best. That, and other similarly related misconceptions can easily form around solar disinfection and must be actively educated out of the paradigm of users.

2.8 Technology Development Challenges

Challenges to development of technology could be in terms of added research and development. For water treatment, techniques for effective removal of emerging contaminants, synthetic chemicals, and pesticides, as well as dealing with spills of chemicals in navigable rivers as well as the development of sustainable treatment methods are some of the challenges. It is the issue of sustainable treatment methods that will primarily be discussed here. A great challenge involving technological development is the need to develop technology that is appropriate, relevant, and sustainable. In regards to sustainable water technologies, development and implementation must make economic and social sense to the stakeholders. Technology implementation that provides safe and affordable drinking water—a crucial human need—can markedly improve the human condition for billions across the globe.

Drinking water treatment technologies have been used and continuously developed over the ages. Greek and Sanskrit writings gave suggestions of ways to treat water as long ago as 2000 BC. They thought perhaps heating water would help, and knew that sand and gravel filtration helped to decontaminate water. However, turbidity was the main criterion used in determining purity, as the knowledge of microorganisms was well beyond their time. The earliest known treatment method was used by the Egyptians around 1500 BC, where they applied chemical alum to contaminated water to remove suspended solids. This is now known as the principle of coagulation (Lenntech 2009). Drawings of this system are found in the tombs of the Egyptian Pharaohs Amenophis II and Ramses II.

Sir Francis Bacon, an English philosopher and scientist was the first to attempt salt water desalination in early 1600, and while his attempts did not work, it opened the door for future endeavors to flourish. It was also in this same time period when Dutch scientists first discovered microorganisms, changing the purpose of water treatment drastically. In India, charcoal was first used as a drinking water treatment technology in the seventeenth century as well. Since then, technologies and techniques have been developed as our understanding of science has deepened. Chemical applications of water treatment (like chlorine filtration) weren't discovered until the nineteenth century, and membrane distillation wasn't discovered until the twentieth century.

The need for continued water treatment development was discussed in the introduction, but can also be highlighted here. The average American living in the United States consumes 185 gallons of water per day. If this number is expanded to include all industrial and agricultural demands, then each US resident uses an average of 1,400 gallons/day. This translates into 255 m^3/capita/year for domestic usage and 1,932 m^3/capita/year for gross consumption including all sectors.

The United Arab Emirates (UAE) withdraws and produces the most potable water of the many countries discussed in Chap. 6 on Solar Distallation. However, for comparison, the UAE has access to only 68% of the treated water that the United States uses per year. As such, many countries do not withdraw nearly enough water to support the same level of economic demand or household consumption as in the United States.

2.9 Technological Implementation—Case Studies

In light of the many challenges presented throughout this book, it is important to remember that drinking water treatment technology has been overall successful so far in relieving water stress for millions (in fact, billions) of people. Some selected examples of technology implementation are given below:

- Natural Filtration—Haridwar and Nainital, India
- Membrane Filtration—Singapore
- Solar Distillation—Mexico/United States border
- Solar Pasteurization—Nyanza Province, Kenya

2.9.1 Natural Filtration

Riverbank and a combination or lake/riverbank filtration are presented as examples of natural filtration. Two case studies are presented:

2.9.1.1 Haridwar, India

Due to religious practices, high population, economic considerations, and low enforcement of best management practices for sanitation, the people of India often draw surface water from polluted sources. This is most evident of those in lower economic strata.

The Uttarakhand state of India is located in the northern regions of the country, nestled against China and Nepal. The region of Uttarakhand is the origin of many of the two major rivers of India, the Ganga and the Yamuna from the snow-capped Himalayas. According to Hindu mythology, there are numerous sacred places along these rivers and their tributaries. People bathe at these sacred places. Yet despite the many rivers which originate in the nearby mountains and the region's relatively low population density of 198 people/km^2 (513 people/mi^2), many of the open water sources are unsafe to drink.

The City of Haridwar is located on the River Ganga where it descends from the mountains to the plains. It is one of the most religious pilgrimage places of India with a permanent population of about 200,000. For religious occasions, an additional 330,000 people come to the city (Sandhu et al. 2010). Uttarakhand Jal Sansthan (UJS) is the agency that supplies water to Haridwar. RBF wells located along the River Ganga or Upper Ganga Canal provide 35% of water to the city. The water supply system in the city was developed in 1927 during the British rule of India. At the end of 2009, there were 16 large-diameter bottom entry wells and 31 vertical wells providing about 64 million liters of water per day. Twelve of these 16 large diameter wells are located on a stretch of about 3.3 km along a narrow strip of land between the River Ganga and Upper Ganga Canal and the spacing among them varies between approximately 200 and 300 m. The distance of these wells to the water body (the canal or the river) varies between 3 and 115 m (Sandhu et al. 2010). Four more large diameter wells are located on an island where the Upper Ganga Canal originated near the Bhimgoda Barrage on the River Ganga. The depths of these wells vary from 7 to 10 m below ground surface. The aquifer is relatively shallow with a thickness of 17 m maximum. The production rate from each well varies between 600 and 2,800 l/min.

A number of water quality studies were conducted since 2005 and Sandhu et al. (2010) summarizes them. Sampling between December 2005 and March 2006 revealed that the dissolved organic carbon (DOC) of the bank filtrate was less than 1 mg/l and the arsenic content was less than 0.01 mg/l. The systems operated under aerobic conditions. All trace metals were below the Indian drinking water standards. The source water of the River Ganga was also low in DOC (0.6–1.2 mg/l) at Haridwar. Dash et al. (2010) showed 2.5 log removal of total coliforms, 3.5 log removal of fecal coliforms, and 0.7 log removal of turbidity during non-monsoon periods (November to June) with a total travel time varying between 84 and 126 days. A log reduction of 1 represents 90% removal of matter tested. During monsoon periods, the river has high turbidity, flow, and microbial contaminants. The log removals for total and fecal coliforms as well as for turbidity were 4.7, 4.4, and 2.5, respectively. During the monsoon period, the travel time of water varied between 77 and 126 days. The abstracted water from the RBF wells at Haridwar is only disinfected (primarily by chlorine) before supply.

2.9.1.2 Nainital, India

While rivers are numerous, the topographic challenges do not always permit easy access to these water sources, and therefore many people rely on the various lakes in the Uttarakhand region. The town of Nainital used to rely on Nainital Lake for its water supply. Recently, bank filtration has been used as the primary source of drinking water supply.

In a case study done in Nainital by the Indian Institute of Technology (Dash et al. 2008) seven pumping wells were developed less than 100 m from the edge of Nainital Lake to test the effectiveness of bank filtration between 1997 and 2006. It was determined that the wells were impacted by groundwater infiltration to the lake, lake seepage, and RBF from one of the perennial inlet drains. This multiple effect scenario was a product of the monsoon season, and therefore the study analyzed water quality in both the monsoon and non-monsoon seasons and compared the two. Lake contamination is caused primarily by the city's antiquated leaky sewage system coupled with direct disposal of sewage into the lake. In an attempt to mitigate these sanitation issues, quick sand filters were used as far back as 1955. However, these filters have since been proven inadequate to match the city's demands or meet the national water quality standards. In order to produce potable water from the polluted lake, advanced treatment methods will be needed. However, the resources to build, operate, and maintain an advanced water treatment plant are not available for many residents in the area. Therefore, natural purification using bank filtration was considered as the best solution to the problem.

Due to the stratification of the unconsolidated detritus material the wells were bored into, it was determined that the water-bearing strata reached a depth of 36 m. Therefore, all seven wells were between 22 and 36 m in depth. Using Darcy's law, the scientists calculated the travel time between the lake and the wells. The monsoon season would yield the shortest travel time as it reflects the highest volume of water. For the wells that were close to the lake shore, it was determined that the water only remained in the ground for 1–2 days (the further wells—84 m from the shore—were calculated to take 11–19 days). This is significantly lower than the assumed value of time required for proper coliform removal during natural filtration, which has been reported to be 10–20 days (Medema et al. 2000).

Despite the short filtration time, and despite the fluctuations in water content during various seasons, it was determined that water arriving at the tube wells had achieved a 4–5 log reduction in total coliform, and a 1.6 log reduction in turbidity. Additionally, suspended solids, bacteria, chemical oxygen demand (COD), and chlorophyll-a were all reduced below detectable limits. The removal of contaminant was so efficient that the water was good for drinking without any further treatment. Conversely, the quick sand filtration used prior to the natural filtration resulted in a coliform count of 2,300 MPN/100 ml, well above the quality standard of a maximum 50 MPN/100 ml coliform concentration. Therefore, the sand filtration has been abandoned in the Nainital region and they have constructed two additional pumping wells to provide clean water to the city of over 50,000 people through the use of bank filtration. The availability of clean water has increased significantly in the region, as the new wells produce 24 Ml/day of pure water where the old sand filters produced only 1 Ml/day of inadequate water.

Therefore, it can be seen that the use of natural filtration is viable and effective for regions with access to alluvial deposits hydraulically connected to a surface water source. It is additionally seen that the use of natural filtration provides consistently high quality water in larger quantities than mechanical filtration despite a significantly longer travel time through the filtering medium.

2.9.2 Membrane Filtration in Singapore

Due to the worldwide shortages of water and growing demand for fresh water supplies, the process of desalinating water has gained more attention. As of now, "Worldwide membrane and thermal desalination capacity is over 11 billion gallons per day from over 12 thousand plants, worth $ 9.2 billion per year, growing at a rate of 12% per year" (AMTA 1–2). Particularly for Singapore, an island nation with limited fresh water and abundant seawater, desalination is an attractive option. Desalinated water has recently found many uses throughout the world including industrial, power plant, military, touristic, and most notable municipal. The Singapore government recently showed its confidence in this technology and that of solar energy by allocating $ 170 million towards its research and development. Scientists are currently working on integrating the membrane distillation processes along with solar, geothermal energy, and heat waste to develop cost efficient energy saving processes for desalinating water.

Major disadvantages of membrane distillation are low productivity and high costs. Researchers in Singapore are working to improve the flux in the process and modify the current techniques. They are using a series of systematic module configurations in an attempt to enhance the total flux. These configurations are made of designs including the baffle, external/inner helix, and can be sieved during module fabrication. They have also brought in two very unique configurations to the module: spacer and twisted modules.

> By implementing these different module designs, the investigators observed an 11–49% increase in flux performance at 75°C with respect to the original, unaltered module. It is interesting that the highest flux attained (49% increase) combined two plastic sieves and the inner helix configuration at 75°C. The generation of turbulence, the increase in effective membrane-surface contact, and the effects of cross-flow possibly account for the improvement in MD performance. (Teoh et al. 2009)

These new module configurations are not only proving to be beneficial, but are sparking interest in both the Middle East and United States for further development.

In reference to the cost issues regarding seawater distillation, the past few decades have shown a significant decrease in the pricing of desalting elements. Due to technological advances, competition, and automation of suppliers worldwide, seawater membrane costs have visibly reduced. "In the last decade, desalting technology has improved significantly and costs have decreased by over 50%" (AMTA 2007). The validity of membrane distillation with the development of new technologies in Singapore and supplier's cost reduction has dramatically improved the technology's feasibility. Membrane distillation's ultimate capabilities may prove to be the wave of the future and if we look to Singapore as an example, we see that the membrane distillation theories discussed in this book are not only relevant, but extremely necessary. We need to diminish our water shortages and fight the increasing fresh water demands while efficaciously utilizing the Earth's resources.

2.9.3 Solar Distillation—Mexico/United States Border

In many dry regions around the world, the lack and growing need for drinking water directly correlates to high solar insulation. In particular, the arid communities along the US-Mexico border face water supply issues that are comparable to those faced by the developing world. As a result, a need for a low cost effective solution to provide safe drinking water is a necessity. The adoption of solar distillation technology could provide clean water for some developing countries worldwide. As an example, in many border cities including Chihuahua (Ciudad Juárez County), New Mexico (Doña Ana County), and Texas (El Paso County) this technology has been used. In these three counties alone, there are over half a million people with very limited water supply and minimal infrastructure development. Municipal water supplies are not up to par with national drinking standards and contain contaminants and high levels of arsenic. "Distillation is the only stand alone point-of-use (POU) technology with NSF (National Sanitation Foundation) certification for arsenic removal, under Standard 62" (Foster et al. 2005).

To acquire safe drinking water, these residents purchased potable water from elsewhere at premium prices and hauled it back home. Solar distillation offers an attainable, on the spot solution to give clean water access to these border families. Over the last decade, solar distillation technologies have been developed in these cities to demonstrate the practicality of this technique along the border and ultimately throughout the developing world. "EPSEA worked closely with NMSU during this initial pilot demonstration, where 40 pilot 3′ × 8′ solar distillers were built by EPSEA and distributed to colonia families and health clinics in West Texas." Studies showed that these solar stills efficiently removed all salts, heavy metals, biological contaminants (*E. coli*, *Cryptosporidium*) and water borne pathogens from contaminated water sources in addition to some pesticides due to the UV rays, high temperatures, etc. "Average water production is about 0.8 l per square meter per sun hour." Daily solar still production for a square meter for two days can be seen in Fig. 2.2.

Progress has continued with this technology and the effectiveness of these solar stills has granted them much attention and financial support.

> Two grants were awarded by the Border Partners in Action (BorderPACT) with the Consortium for North American Higher Education Collaboration to disseminate solar stills distributed to 27 Mexican families in Chihuahua. EPSEA also won a community challenge grant from EPA to distribute stills to 80 families in Texas and New Mexico from 2000 to 2002. (Foster et al. 2005)

These solar stills work by the simple concept of evaporation and condensation, which were described in more detail earlier. After the water has evaporated, all

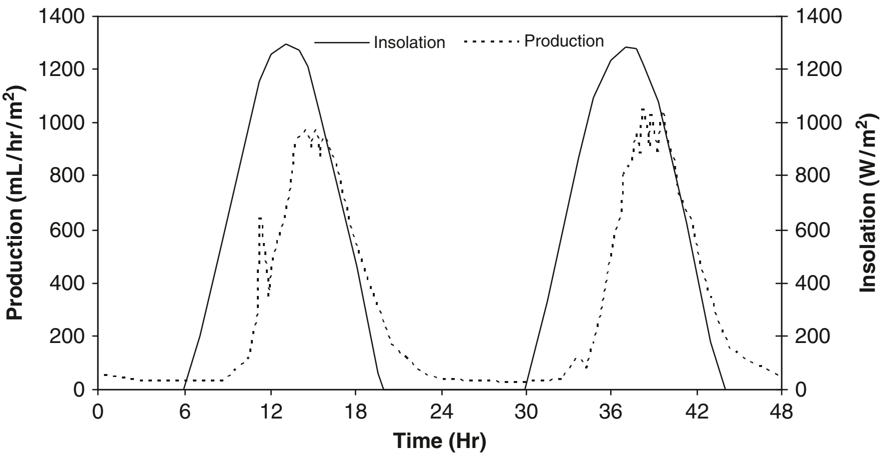

Fig. 2.2 Solar insolation and measured solar distillate production over 48 h in southern New Mexico; notice how distillate production lags insolation and continues even after sunset. (After Foster et al. 2005)

contaminates are left behind and the evaporated water is not only purified, but desalinated as well.

> Typical production efficiencies for single basin solar stills on the Border are about 60% in the summer and 50% during the colder winter. Single basin stills generally produce about 0.8 l per sun hour per square meter. (Foster et al. 2005)

Still design has significantly improved over the last few years. What began as a silicone membrane lined still in the mid 1990s, converted to aluminum to avoid beading of the water droplets, and is now comprised of ABS Plastic by a company coined SolAqua. Outgassing issues were addressed with new proprietary inner membrane materials and the distillation technology has shown significant progress. "The technology has now evolved to the point where with large manufacturing volumes unit costs could be greatly reduced by a factor of three or more in the future" (Foster et al. 2005).

Additionally user response has been quite positive. Most found it cheaper to purchase a low priced solar still rather than traveling to purchase bottled water at high prices. "Solar still savings were approximately $ 150–200 a year per household instead of purchasing bottled water" (Foster et al. 2005).

> Many families in the U.S. colonias (border communities) often spend from $ 8 to 12 per week on bottled water. Likewise, in northern Mexico families often spend $ 3–5 per week on purified water. This represents an investment of anywhere from $ 150 to 600 per year for bottled water. (Foster et al. 2005)

Thus the payback period of a still versus bottled water is only 2–3 years, with savings amounting to thousands of dollars over a decade. "The levelized energy cost of solar distilled water is about US$ 0.03 per liter, assuming a ten year still lifetime" (Foster et al. 2005).

In some cases, owners highly valued the idea of a clean, affordable technology that left a minimal carbon footprint on the Earth. A few drawbacks on the technology however, are that the stills are not producing optimal amounts to meet production needs in the winter.

> Generally, it appears that for most Border households about 0.5 m^2 of solar still is needed per person to meet potable water needs consistently throughout the year. Those households with insufficient wintertime still water production typically had 0.35 m^2 or less of still area per person. (Foster et al. 2005)

Only about 40% of users are receiving sufficient water production all year round. (Foster et al. 2005). However, supplemental water cost is still far less than residents having to purchase bottled water throughout the summer when premiums are at their highest. As of now, EPSEA has expanded its distribution to and began solar stills implementation in Australia, the South Pacific, Mexico, and Guatemala. It is evident that this technology and these solar stills allow a practical, relatively inexpensive way for residents to obtain drinking water. As seen in these overall successful borderland city cases, solar stills have astounding worldwide potential to address potable water needs and ultimately, saving lives.

2.9.4 Solar Pasteurization—Nyanza Province, Kenya

As was mentioned earlier, 1.1 billion people do not have access to safe drinking water and much of Africa's population contributes to this astounding statistic. About half of the population of sub-Saharan Africa does not have access to clean water. Although there are insufficient water sources in most regions of Africa, there is an abundance of sunlight. This excess sunlight can be transformed into the energy required for solar water pasteurization through the use of solar cookers. Ultimately, this solar energy can heat water to temperatures that kill harmful microbes and provide safe, clean drinking water for the people.

> What is not well known is that contaminated water can be pasteurized at temperatures well below boiling…Used alone, boiling and solar [pasteurization] were about twice as effective as chlorine [disinfection], and when used together they were four times as effective. (SCI 2009).

Currently, there is a Sunny Solutions program which began in Africa in 2003, being implemented in the Nyakach region, Nyanza Province, in western Kenya. As a part of this program, women can choose to use the CooKit Solar Cooker to prepare food and decontaminate their own water. In this particular area of Kenya, there is a very high occurrence of typhoid fever as well as bacterial and amoebic dysentery. Additionally, their wells and streams are highly contaminated with *E. coli*. However, with the use of the CooKit solar cookers, there has been a substantial decrease in diarrheal diseases and many other water borne diseases primarily caused by *E. coli*.

> The Nyakach solar cooks and village leaders have been taught how to use innovative water testing methods, Colilert tubes and Petrifilms to test their water before, and after solar pasteurization. The package of water testing materials, CooKit, and WAPI, combine to address two main problems in developing countries: lack of wood for cooking and unsafe water for drinking. (Metcalf 2009)

Both the Colilert (www.palintest.com) and Petrifilm (http://solutions.3m.com/wps/portal/3M/en_US/Microbiology/) water sampling methods enable people to accurately and cheaply test water. These methods provide quality microbiology and give water testing abilities to the 72 districts of Kenya.

Results of these women and leaders properly utilizing and benefiting from the Sunny Solutions proposition seems to show these solar cookers being the solution to making clean water and safe food available to the poorest of the poor. "When… I visited the homes of 16 [CooKit users] in July 2004, we found that each woman was heating water in a CooKit when she was not cooking, and was pasteurizing 5–10 l/day." A survey taken in mid-July of 2005 indicated that amongst the 47 Kenyan families chosen, solar pasteurization was quickly adopted and the use of the CooKits provided a visible reduction in diarrheal contamination among small children (Metcalf 2009). While pasteurization has been accepted in the food industries for decades, it has been seemingly left out of discussions regarding unsafe water.

> From published data and our own experiments, we established that heating contaminated water to 65°C will pasteurize the water and make it safe to drink. (Metcalf 2009).

The success of the solar pasteurization projects in Kenyan validates the potential for this type of technology and reflects highly upon its need in developing countries. Solar energy is often the only energy source for people living in remote areas in developing countries. Solar pasteurization can thus provide safe drinking water in most cases where water does not contain contaminants such as inorganic chemical pollutants or arsenic.

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