Chapter 38

Technologies to enhance sustainable groundwater use

Roger Sathre[1,2]

[1]*Institute for Transformative Technologies, Berkeley, CA, United States,* [2]*Linnaeus University, Växjö, Sweden*

38.1 Technology levers to enhance groundwater security

Groundwater is increasingly important to human welfare, and dependence on groundwater resources is growing. However, renewable groundwater supply is ultimately limited, and overexploitation is leading to depletion and contamination of aquifers (Mukherjee et al., 2020). This chapter discusses a wide range of technology interventions aimed at improving groundwater security.

First, technologies for groundwater mapping are described, with the goal of understanding aquifer processes leading to improved groundwater management. Knowledge gained from groundwater mapping can be used to manage the recharging of aquifers, enabling higher rates of rainwater capture and more renewable groundwater. Groundwater mapping also informs the management of saline groundwater intrusion, to eliminate aquifer contamination that will be an increasing problem due to sea-level rise.

A range of technologies can reduce groundwater demand by improving water-use efficiency, so that less water is needed to achieve the same ends. In the agricultural sector, many irrigation efficiency improvements are available to reduce the quantities of water extracted and applied to fields. However, the net groundwater implications of these technologies are complex, as excess irrigation water often contributes to groundwater recharge. In the household and municipal sector, end-use water efficiency improvements can reduce final water demand, and distribution improvements can reduce water losses and extraction requirements. In the industrial sector, global best practice efficiency improvements can strongly reduce water demand for many industrial processes.

Many technologies are available to improve the quality of groundwater that is contaminated by impurities. Many regions possess abundant brackish groundwater that is presently unutilized, and emerging technologies can desalinate this water at much lower cost and energy use than seawater desalination. In regions where groundwater is contaminated by arsenic and fluoride, purification technologies are available to remove these natural toxins. Groundwater in some regions contains biological pathogens due to inadequate disposal of fecal waste, and a range of technologies can be used to make this water safe for consumption.

While many regions suffer from inadequate groundwater quantity or quality, other regions, including much of sub-Saharan Africa, possess abundant clean groundwater that is currently underutilized due to economic water scarcity. In these areas, improved technologies are needed to access and extract the groundwater. Low-cost methods for digging or drilling wells, and for pumping groundwater to the surface, can improve the well-being and economic development of people in these regions.

Many technology levers already exist that could enhance the sustainable use of groundwater resources, and others are being developed to meet growing needs. Widespread deployment of these technologies has the potential to significantly improve water security conditions for people around the globe. Concerted effort is needed to enable the economic, political, and logistical requirements of such deployment, so that renewable groundwater resources contribute maximally to long-term water security and resilience.

38.2 Groundwater mapping and management

The technology set for groundwater mapping seeks to understand the broad hydrogeological landscape, to inform better management of groundwater resources. Comprehensive groundwater mapping can be used to determine the location

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and quality of groundwater, as well as aquifer recharge mechanisms that affect the sustainable quantities of groundwater available for extraction and use. A primary focus of groundwater mapping is on the mechanisms of sustainable groundwater cycling, to facilitate long-term utilization and enhancement [through, e.g., managed aquifer recharge (MAR)] of sustainable groundwater resources. It may also be used to temporarily increase water supply by enabling the precise siting and one-time extraction of remaining fossil water aquifers. India [CGWB (Indian Central Ground Water Board), 2019] and Ethiopia [ATA (Ethiopian Agricultural Transformation Agency), 2019] have conducted pilot groundwater mapping studies in areas with different hydrogeological terrains, with intentions to map the entire countries and improve resource usage.

A range of techniques is used to provide primary data for groundwater mapping (Klee et al., 2015). Data are gathered across many scales, from in situ underground sampling, to surface-based sensing techniques, to remote sensing from aircraft or satellites. Multiple techniques are commonly used in parallel to combine information on different characteristics, to generate more robust maps. Numerous sensing technologies have been developed based on acoustic, electric, or magnetic principles, to provide data on geological structures, surface morphology, and their hydrologic characteristics:

1. Seismic surveys are made by propagating acoustic energy through the ground, and tracking seismic refraction of compression waves that show increasing velocity with density. Seismic surveys provide information on the internal structure of aquifers such as clay and silt layers that limit the overall vertical permeability.
2. Electrical resistivity techniques (such as electrical resistivity tomography) induce an electrical current in the ground, and the resulting electrical potential at different locations is used to measure the variation in ground conductivity, or its inverse, resistivity. Different materials, and the fluids within them, will show different abilities to conduct an electric current. Electrical resistivity methods are often used for well siting and for locating suitable sites for percolation fields in hard rock areas.
3. Ground penetrating radar emits high-frequency electromagnetic waves into the ground and receives and interprets the microwave energy reflected back to the surface from different underground materials, to provide detailed subsurface cross sections.
4. Airborne transient electromagnetic systems can be fitted to helicopters or fixed-wing aircraft or drones and are used to map the apparent conductivity of the ground.
5. Time domain electromagnetic methods can map the shallow subsurface but are susceptible to interference from pipelines and power lines. In this method, current pulses are sent through a large square wire loop on the ground. The decay of current at the end of each pulse generates a magnetic field that enters the ground. Eddy currents induced by this changing magnetic field generate secondary magnetic fields in the ground. The amplitude and rate of decay of these secondary fields are measured at the surface and analyzed to determine underground characteristics.
6. Frequency domain electromagnetics are typically used to measure variations in lateral conductivity along linear or gridded profiles.
7. Direct physical surveys can be made of existing wells to determine the quality of groundwater as well as the depth and fluctuation of the water table. This is typically done manually (if at all), providing only intermittent data points. The development and deployment of a distributed network of digital sensors to provide real-time monitoring of well water characteristics throughout the region, could be an important advance for sustainable groundwater management. Hydrogeological data from multiple sources could then be integrated to form the basis of an online map of real-time groundwater quality and quantity.

38.3 Managing aquifer recharge

As groundwater mapping provides greater understanding of subsurface conditions, this knowledge can be applied by MAR technologies that aim to increase the rate of groundwater recharge to allow greater groundwater extraction without risk of water table decline. While some deep aquifers contain fossil water that was stored long ago and does not circulate unless accessed and extracted by wells, most aquifers are dynamic and receive newer water via recharge mechanisms while losing older water via groundwater pumping and natural discharge to rivers and oceans. While groundwater extraction is increasing, the rate of natural aquifer recharge is diminishing in many regions, due to rapid urbanization and land use changes that reduce infiltration of rainwater into the soil.

MAR is achieved by reducing the fraction of rainwater that runs off the land surface, thus increasing the fraction that infiltrates through the land surface and enters the soil. This is typically implemented through engineered structures

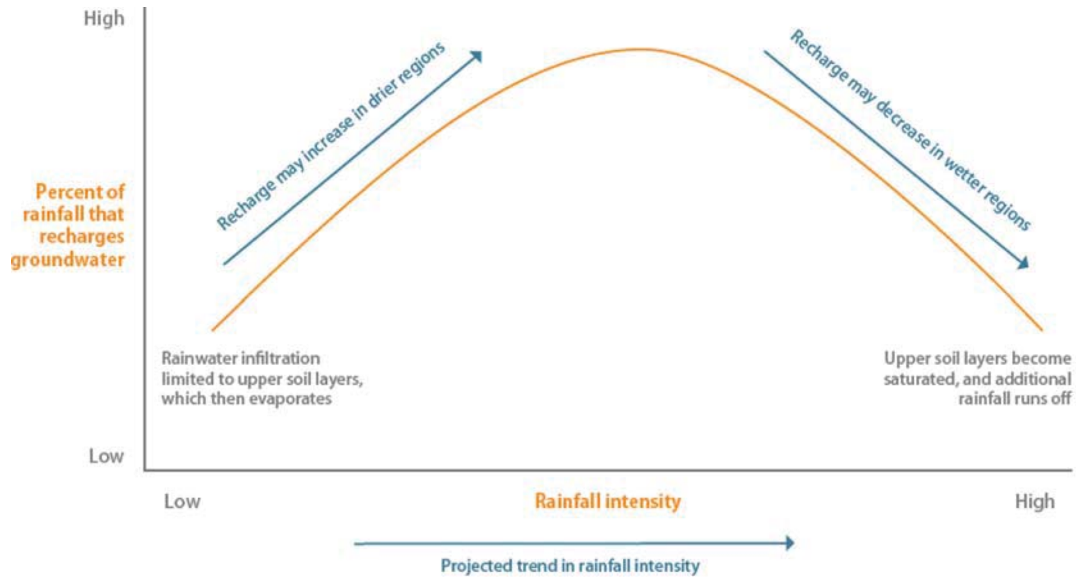

FIGURE 38.1 Rainfall intensity is projected to increase due to global climate change, which may have variable effects on groundwater recharge. *Credit: ITT (Institute for Transformative Technologies), 2018. Technology Breakthroughs for Global Water Security: A Deep Dive into South Asia. Institute for Transformative Technologies, Berkeley, CA [ITT (Institute for Transformative Technologies), 2018].*

that slow the downstream flow of surface runoff water, allowing more of it to infiltrate into the ground [CGWB (Indian Central Ground Water Board), 2007]. A wide range of structures is available at varying scales, including farm-level swales, check dams, percolation tanks and ponds, dams, and barrages (Gale, 2005).

MAR is suitable only in particular locations, because it requires three conditions: the availability of uncommitted surface water, underground storage space, and the demand for groundwater (Shah, 2008). In drier regions the amount and timing of rainfall limit the amount of runoff that may be harnessed to recharge groundwater. In regions with unsuitable geology, even if seasonal water is plentiful, there may be inadequate aquifer porosity to store significant water or there may be natural barriers between the surface runoff and underground aquifer.

In closed river basins, where all available surface water is allocated and used, MAR will not increase total water supply even if local runoff and geology are suitable, because an upstream user's gain will lead to a downstream user's loss. Furthermore, the effects of future climate change on aquifer recharging are uncertain. The amount, timing, and intensity of precipitation are projected to change, though its effect on the partition of rainwater into runoff and infiltration will vary by location (see Fig. 38.1).

Nevertheless, where conditions are suitable, MAR may contribute significantly to regional groundwater security by increasing allowable sustainable groundwater extraction rates. Ideally, groundwater should be considered a storage reservoir to smooth fluctuations and allow flexible access, not a stock to be depleted.

38.4 Managing saline groundwater intrusion

The technology set for managing groundwater salinity is an increasingly important application of groundwater mapping. Fresh groundwater aquifers are often surrounded by saltwater on one or more sides or underneath. Since freshwater is less dense than saline water, it tends to flow on top of the surrounding or underlying saline groundwater. Under natural conditions the boundary between freshwater and saltwater maintains a stable equilibrium. Under some circumstances the saltwater can move (or intrude) into the freshwater aquifer, making the water nonpotable. When freshwater is pumped from an aquifer that is near saline groundwater, the boundary between saltwater and freshwater moves in response to the pumping. If this continues, unusable saline water will be pumped up from the well.

Freshwater aquifers are naturally recharged by rainwater, and the recharge rate can be manipulated by MAR. Thus there is dynamic interplay between freshwater withdrawals, freshwater recharge, and surrounding saline aquifers. Rising sea levels due to climate change are slowly increasing the gradient of saline water, although coastal aquifers are more vulnerable to groundwater extraction than to predicted sea-level rise (Ferguson and Gleeson, 2012).

Techniques are under development to manage saline groundwater intrusion. Actions, such as controlling the rate and depth of groundwater extractions and augmenting freshwater recharge by MAR, can reduce or eliminate undesired saline intrusion. Skimming wells can also be used to sustainably exploit fresh groundwater lenses that overlie native saline groundwater (Saeed and Ashraf, 2005). The freshwater lenses are renewed through percolation of rain and irrigation water. Skimming wells are designed and operated to minimize the mixing between overlying freshwater and underlying saline water.

Successful management of saline groundwater intrusion requires a deep understanding of aquifer dynamics and how they may be manipulated. The tools of groundwater mapping provide this essential knowledge of the hydrogeological landscape.

38.5 Improving groundwater-use efficiency

By increasing the efficiency with which water resources are used, more utility can be obtained from each unit of available groundwater. Different technology sets are relevant for the agricultural, household, and industrial sectors.

38.5.1 Improving irrigation and agricultural efficiency

Irrigation of cropland is the greatest user of groundwater in many regions. Irrigation efficiency is typically measured in terms of the percentage of applied water that is taken up by the roots of growing crops. However, the net groundwater implications of improving irrigation efficiency are complex, because much of the applied water that is not used by crops infiltrates into deeper soil horizons and recharges groundwater stocks [Perry, 2007; FAO (Food and Agriculture Organization of the United Nations), 2017].

A range of existing technologies and methods can be used to increase water-use efficiency in irrigation, with varying costs. The most common practice globally is surface irrigation, where water is applied directly to the surface of a flat or gently sloped field. Two promising options for improving efficiency of surface irrigation are precision land leveling and tensiometer-based irrigation scheduling. Two important alternatives to surface irrigation are sprinkler irrigation and drip irrigation, which are increasingly used for higher value crops for increased control and production as well as for water savings.

With simple surface irrigation techniques, less than half of the applied water is typically transpired by the growing crops, and a small percentage is lost to nonproductive evaporation. The remaining water infiltrates into deeper soil layers and becomes groundwater that can be recycled by wells. Depending on rainfall and soil characteristics, farm field infiltration can comprise a significant source of groundwater recharge (see Fig. 38.2). From a basin-level perspective, therefore, the leaked water is not truly lost, because it can be abstracted as groundwater and used (Grafton et al., 2018).

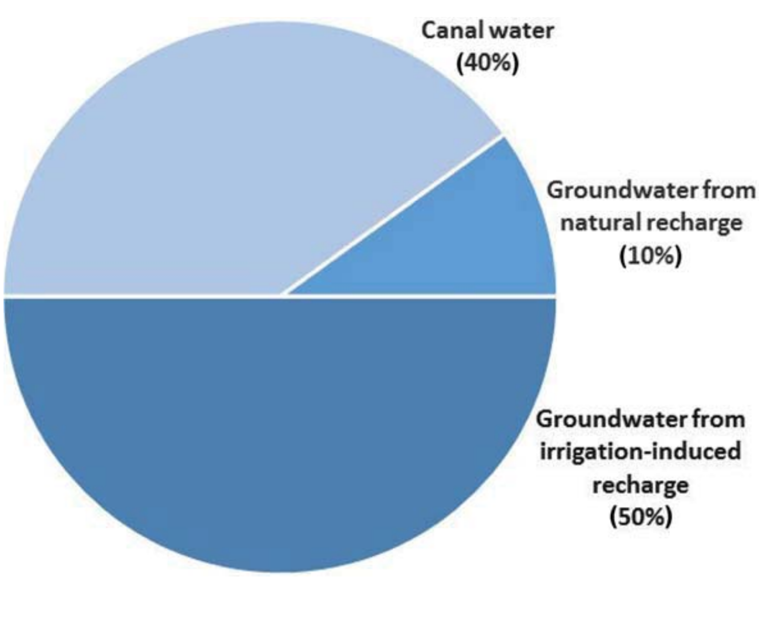

FIGURE 38.2 Half of irrigation water in Pakistan's Punjab province is from groundwater recharged through irrigation water infiltration. *Credit: data from World Bank, 2005. Pakistan's water economy running dry (World Bank, 2005).*

While irrigation water-use efficiency improvements focus on reducing water inputs to agriculture, there are numerous other agricultural improvements that increase crop production without directly affecting water use. This indirectly enhances groundwater security by increasing overall agricultural production, thus reducing the need for additional irrigation water to satisfy the growing demand for food. Farm-level management may be improved by stronger agricultural extension services to inform about and advocate higher yielding, water conserving agricultural crops and techniques. Foresighted policy instruments, including appropriate subsidies and taxes on inputs such as seeds, fertilizers, and water, can stimulate more rational consumption patterns within the agricultural sector.

There is great scope for increasing agricultural yields in low-achieving irrigated regions, via appropriate agricultural extension activities and other interventions. Many farmers could raise water productivity by adopting proven agronomic practices such as soil fertility maintenance and pest management (Molden and Oweis, 2007). The highest gains in water productivity are likely in areas where yields are still low, warranting a development focus on regions with lower agricultural performance.

38.5.2 Improving household water distribution and use efficiency

In regions that rely on groundwater for household water supply, improving the efficiency of delivering and using groundwater resources can be an important lever for sustainability. Much water is lost to leakage during municipal distributions. Effectively managing physical losses (leakage) in distribution systems requires active control measures, speed and quality of repairs, and effective pressure management. Globally, substantial experience has been accumulated in successfully distributing continuous water supply throughout large cities. Best practice recommendations have been developed for broad actions to reduce nonrevenue water and intermittent water supply, including complete metering of production and consumption, improved billing and collection, and identification and repair of visible and invisible leaks [ADB (Asian Development Bank), 2010].

Metering of water flows at multiple points throughout a municipal water utility system is important to managing municipal water flows and identifying leakage. Modern flow metering, pressure management, and data capture technologies can quickly identify burst pipes and estimate the gradual accumulation of smaller leaks (Simbeye, 2010). Flow meters can only detect the general area of leakage but cannot pinpoint the exact location of a leak. For this, sensors such as ultrasonic noise loggers, leak noise correlators, and ground microphones are used to detect the exact location of the leakage for repair.

Another important tool to reduce urban water loss is pressure management, as leakage rates are very sensitive to system pressure. The rate of leakage in water distribution networks is a function of the pressure applied by pumps or gravity. There is a direct physical relationship between the water pressure, and both slow leakage rate and the frequency of burst pipes. The most common and cost-effective measure is automatic pressure reducing valves that are installed at strategic points in the network to reduce or maintain network pressure at a set level. Other pressure management measures include air relief valves to release negative pressures or air bubbles in a pipeline, variable speed controllers, and break-pressure tanks.

Notwithstanding the accumulated global best practices for urban water distribution, many municipal utilities are currently challenged to provide their inhabitants with continuous supply of high-quality water. Intermittent water supply, in particular, is impeding the adoption of improved water utility management practices such as metering and automated control systems. These best practice approaches require continuous water supply and cannot be applied where pressure is supply-driven rather than demand-driven (Kumpel and Nelson, 2016).

Another technology set for reducing groundwater demand aims to use less household water. Improved appliances are commercially available that use less water than conventional appliances that perform the same function. Examples include low-flush toilets, low-flow sinks and showers, and water-efficient clothes washing machines. These water-efficient devices are gaining increasing attention in some industrialized regions facing water constraints. In the current emerging market context, water conserving flush toilets may play a role in reducing groundwater demand, through replacing older flush mechanisms in existing buildings and installing high-efficiency flush toilets in new construction. Though challenging, increasing the distribution and usage efficiency of household water is a significant lever for improving groundwater sustainability.

38.5.3 Improving industrial water-use efficiency

In addition to farm and household use, another important demand for groundwater is the industrial sector. Groundwater is commonly used by industries, due to its accessible cost and reliable supply (Fig. 38.3). Particularly water-intensive

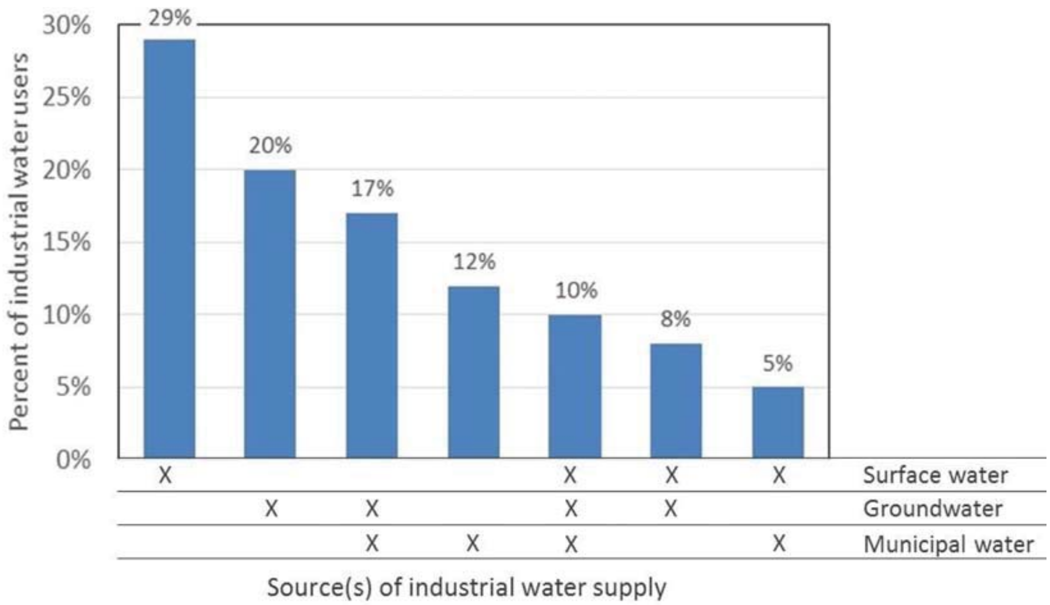

FIGURE 38.3 Sources of industrial water in India. Groundwater is used by 55% of industrial water users in India. *Credit: data from Perveen, S., et al., 2012. Water Risks for Indian Industries: A Preliminary Study of 27 Industrial Sectors. Federation of Indian Chambers of Commerce and Industry (FICCI) and Columbia University Water Center (CWC) (Perveen et al., 2012).*

industries include steel, textiles, pulp, and paper. In regions of groundwater stress, industrial water demand competes with household and irrigation water demand for limited supply.

Industrial production and its associated water use are increasing rapidly. Many industrial processes require water for various purposes such as cooling and washing. Industrial water-use efficiency in many groundwater-stressed regions is quite low, and the adoption of global best practices would significantly reduce industrial water use. In recent decades, as water constraints have been felt in various parts of the world, much effort has been expended globally to devise industrial processes that conserve water. Implementation of this global best practice could significantly reduce future demand for industrial groundwater, while reducing the quantity and improving the quality of industrial wastewaters.

38.6 Purifying contaminated groundwater

Groundwater quality problems can be caused by chemical, physical, microbiological, or aesthetic issues. Here we discuss removing salt from brackish groundwater, removing arsenic and fluoride from groundwater, and killing biological pathogens that are present in groundwater due to inadequate sanitation methods.

38.6.1 Removing salt from brackish groundwater

Desalination is a technology set that seeks to make freshwater from saline water sources such as seawater or brackish water. The salt content of water is typically measured in grams of total dissolved solids (TDS) per liter of water. While there are no definitive standards, water is generally considered potable when it contains TDS less than about 1 g/L. The salinity of ocean water averages 35 g/L globally. Many regions possess abundant groundwater that is brackish, with TDS up to about 5 g/L.

There are numerous desalination technologies, which can be divided into four major categories depending on the driving force of the process: thermal, pressure, electrical, and chemical (Miller, 2003; Youssef et al., 2014; Subramani and Jacangelo, 2015).

1. Thermally driven systems use evaporation and condensation at different temperatures and pressures as the main process to separate salts from water. In these systems, heat transfer is used to either boil or freeze the feedwater to convert it to vapor or ice, so that salts are separated from the water. The most common thermal processes include the multistage flash process and the multieffects distillation process (Shatat and Riffat, 2014). Other thermally activated systems include vapor compression distillation, humidification–dehumidification, solar distillation, and freezing.

2. Pressure-activated systems use a pressure gradient to force water through a semipermeable membrane, leaving salts behind. In recent decades, membrane technologies have matured and most new desalination installations use membranes. Of these, the reverse osmosis (RO) process is the most common; others include forward osmosis and nanofiltration.
3. Electrically activated systems take advantage of the charged nature of salt ions in solution, by using an electric field to remove ions from water. The most common configuration is electrodialysis (ED), which currently accounts for about 4% of global desalinated water production. An emerging technology is capacitive deionization (CDI).
4. Chemically activated desalination systems include ion-exchange desalination, liquid−liquid extraction, and gas hydrate or other precipitation schemes. There are numerous alternate desalination processes that are technically possible but are limited by economic or practical issues (Miller, 2003).

Cost of energy supply strongly affects the cost of desalination, and a major source of variability is the form of energy that drives the desalination process, such as heat, pressure, electrical, or chemical (Rao et al., 2016). In general, thermal desalination uses large amounts of heat, RO uses much smaller amounts of electricity, and ED uses even less electricity but is limited to low-salinity feedwater (see Fig. 38.4). The overall cost of the various processes also varies and is heavily dependent on scale. Larger facilities are far less expensive per cubic meter of freshwater.

Membrane-based seawater desalination technologies are approaching theoretical limits of energy efficiency and are already used at commercial scale for industrial and domestic use (Elimelech and Phillip, 2011). Although minor incremental efficiency improvements may still be gained, it is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape.

For brackish groundwater, there are major opportunities for significant reductions in desalination cost and energy use through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feedwater—less energy is fundamentally needed to desalinate brackish water, compared to seawater. Electrically driven techniques, such as ED and CDI, are limited to low-salinity feedwater, but potentially cost less and require less energy than pressure or thermal techniques (see Fig. 38.4). ED and CDI technologies use less energy because they transport the (relatively few) dissolved salt ions out of the feedwater, rather than

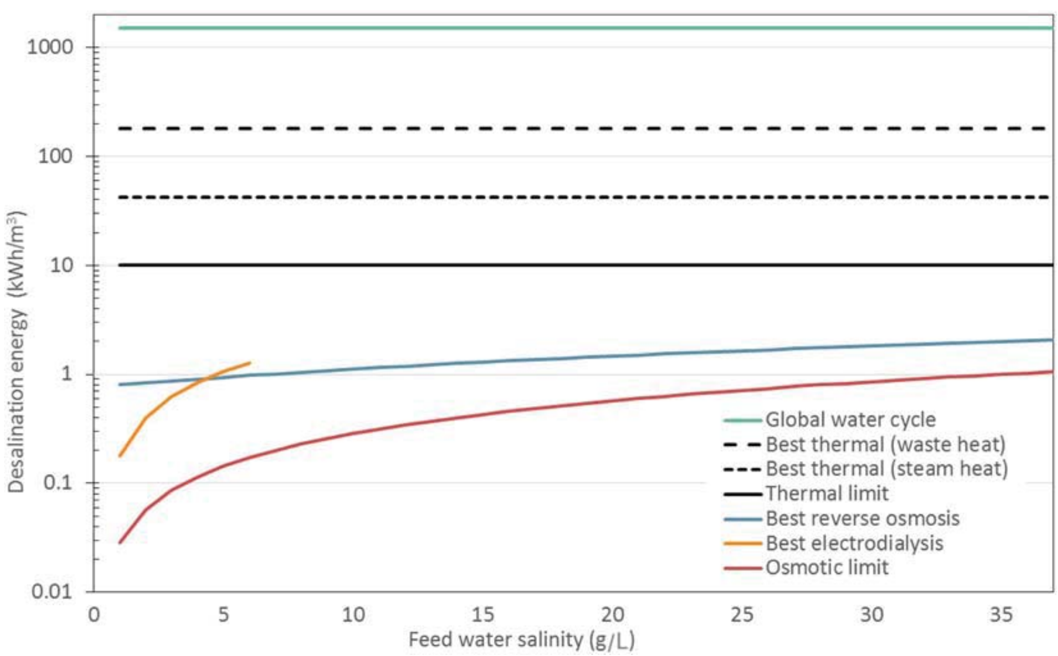

FIGURE 38.4 Energy use for desalination (kilowatt-hour per cubic meter of freshwater) as a function of feedwater salinity (grams TDS per liter of feedwater) for various desalination processes. Note vertical axis is logarithmic. *TDS*, Total dissolved solids. *Credit: data from Cerci, Y., et al., 2003. Improving the thermodynamic and economic efficiencies of desalination plants: minimum work required for desalination and case studies of four working plants. In: Program Final Report No. 78. Mechanical Engineering, University of Nevada, Reno (Cerci et al., 2003); Fritzmann, C., et al., 2007. State-of-the-art of reverse osmosis desalination. Desalination 216, 1−76 (Fritzmann et al., 2007); Elimelech, M., Phillip, W.A., 2011. The future of seawater desalination: energy, technology, and the environment. Science 333, 712−717; Shatat, M., Riffat, S.B., 2014. Water desalination technologies utilizing conventional and renewable energy sources. Int. J. Low Carbon Technol., 9, 1−19.*

transporting the (plentiful) water molecules away from the salt as in thermal and pressure technologies (Suss et al., 2015). The electrical current required for ED and CDI is proportional to the amount of salt removed (Knust et al., 2014). ED and CDI are highly efficient for desalinating feedwater on the dilute end of the brackish water range (0.6−4 g/L TDS).

38.6.2 Removing arsenic from groundwater

In parts of the world the underground geological formations comprise minerals containing arsenic, resulting in groundwater containing this natural toxin. Consumption of water, including both drinking water and cooking water, with elevated arsenic levels over a prolonged period can result in serious health conditions, including skin lesions, hyperkeratosis, melanosis, and cancer in different organs, which in some cases is fatal. The probability and severity of health effects increase with exposure level and duration.

The most common current arsenic removal technologies can be grouped into five categories: oxidation, ion-exchange, activated alumina, membrane, and coagulation/coprecipitation/adsorption (Rahman and Al-Muyeed, 2009). Some promising technologies, such as electrocoagulation, are emerging. Each of these technologies has trade-offs in terms of feed water characteristics (i.e., pH, concentrations of arsenic, iron, phosphate, silicate, and calcium); operation and maintenance complexity; and aesthetic water quality. The arsenic concentration of the feed water is a key factor influencing the removal efficiency and cost. Technologies that demonstrate high removal efficiencies when treating moderately arsenic-contaminated water may not be as efficient when treating highly contaminated water (Shan et al., 2018).

In terms of effectiveness, oxidation−filtration and ion-exchange technologies have shown poor efficacy, while zerovalent iron and other adsorption technologies work well. Users give coagulation−coprecipitation−filtration technologies mixed reviews (Amrose et al., 2015). A variety of arsenic removal technologies are available at the community and household level. The most widely used household arsenic removal systems use zerovalent iron, such as the SONO filter. However, many household users complain of low-flow rate and occasional clogging. Community-level treatment typically exists as column filters containing media such as activated alumina, granular ferric hydroxide, or hybrid anion exchange.

A major concern regarding arsenic removal technologies is that the collected arsenic must be disposed of after it has been removed from a water source. Unfortunately, this disposal practice is often unregulated and arsenic waste is sometimes dumped in ponds or open fields. The arsenic concentration of these wastes varies widely but can reach 7.5 g/kg (Amrose et al., 2015), roughly a million times more concentrated than the maximum allowable arsenic concentration in safe drinking water. An effective large-scale arsenic removal program will require a method for responsible disposal of the collected arsenic.

38.6.3 Removing fluoride from groundwater

Fluoride is another naturally occurring element that is present in some groundwater. Fluoride contamination is highly prevalent in hyperarid and humid areas of Asia and Africa. Various defluoridation techniques have been developed, including coagulation, adsorption, ion-exchange, electrochemical, and membrane-based methods (Mumtaz et al., 2015). The coagulation technique uses reagents, such as aluminum salts, lime, calcium and magnesium salts, polyaluminum chloride and alum to precipitate fluoride through a chemical reaction in which the precipitated fluoride coagulates and can then be removed. The Nalgonda technique is a coagulation−defluoridation technique that has seen limited acceptance because it is relatively difficult to maintain and operate. This is a common problem with defluoridation technologies.

Adsorption processes involve continuously cycling fluoride-contaminated water through columns containing an adsorbent, such as bone char, activated alumina, activated carbon, activated bauxite, ion-exchange resins, fly ash, super phosphate and tricalcium phosphate, clays and soils, synthetic zeolites, and other adsorbent minerals. The cyclic sorption tends to aggregate and concentrate the fluoride, which can then be disposed of safely.

Electrochemical processes include electrocoagulation and electrosorptive techniques. During electrocoagulation processes, Al^{3+} ions are released from aluminum electrodes through an anodic reaction, which generate aluminum hydroxides that adsorb fluoride ions near the electrodes, resulting in a fluoride complex that can then be easily removed. Electroadsorptive techniques only differ from adsorption techniques in that an electric field is applied to the adsorbent bed, which increases its adsorption capability.

The use of membrane technologies in defluoridation is relatively new and includes RO, nano- and ultrafiltration, ED, and Donnan dialysis. These processes typically have high operational costs compared to other defluoridation techniques (Ayoob et al., 2008).

38.6.4 Killing biological pathogens in groundwater

Microbial pathogens are often present in groundwater due to inadequate sanitation practices that allow fecal pathogens to enter groundwater. Pathogens that are present in groundwater must be killed, deactivated, or physically removed before the water can be safely consumed. There are numerous ways this can be achieved at various scales, including through chemical, thermal, radiation, and filtration methods (Gadgil, 1998; Amrose et al., 2015)

Several of these technologies are often combined together to achieve better drinking water quality. For example, ceramic filters can be lined with silver and copper nanoparticles to ensure all pathogens are killed and filtered out. Another example is chloramination, which is the combined use of chlorine and ammonia. Chlorine is the most widely used water disinfectant, while ozone is the second most widely used.

Chemicals used as disinfectants will sometimes react with naturally occurring chemicals in a water source to produce by-products that are harmful to human health. Some common by-products are bromate, chlorite, haloacetic acids, and trihalomethanes. Many of these by-products are toxic and/or carcinogenic (US EPA, 2018). Activated carbon filters may be used secondarily to adsorb and remove some of these by-products.

38.7 Improving groundwater access

While physical constraints to water quality or quantity limit some people's access to groundwater, economic constraints limit access by other households and farms. Of particular concern is the lack of access to groundwater for agricultural irrigation in sub-Saharan Africa. Most farmers in this region use low-yielding and highly variable subsistence rain-fed farming methods, despite the presence of abundant shallow groundwater. Access to irrigation is a critical constraint to increasing agricultural productivity for smallholder farmers in sub-Saharan Africa. With irrigation, farmers can increase crop yields, produce more consistent harvest, diversify their portfolio toward higher income crops, and increase the total number of harvests in a given year. While eliminating economic water scarcity in this context will require broader socioeconomic interventions, appropriate technologies for low-cost well drilling and water pumping may make important contributions.

38.7.1 Well digging and drilling

Well drilling to access groundwater played a major role in the Green Revolution and is an important part of water supply development in many regions. Millions of borewells have been drilled since the 1960s, and many regions have developed strong local expertise in siting and drilling wells, as well as in producing and maintaining drilling equipment. This expertise is currently lacking in most parts of sub-Saharan Africa, as well as in parts of South Asia with limited agricultural intensification. A variety of drilling technologies are available, depending on soil characteristics and required depth.

The difficulty and cost of digging wells vary as functions of water table depth and soil formation. When groundwater is available at depths less than 4 m, manual digging or drilling is adequate. Shallow hand-dug wells are inexpensive, with the primary cost being the digger's time. For deeper wells, numerous manual drilling techniques have been developed to produce shallow borewells in favorable geology, including sludging and augering. Manual drilling techniques, often involving community participation as labor, are typically slow and limited in the geological strata they can drill. Mechanized drilling of deeper wells is typically unaffordable for subsistence farmers. This type of drilling is typically conducted with portable diesel-powered rigs, such as percussion and rotary percussion methods. Powered mechanical rigs are expensive (> \$100,000) and have limited mobility to reach remote areas. They are able to effectively drill through most geological features and are relatively quick to create a well but are expensive and have high costs for capital equipment, fuel, and labor.

Current well drilling technologies suffer from high cost, limited portability, slow drilling rate, and/or limited geologic suitability. To expand groundwater opportunities to rural populations facing economic water scarcity, a drilling technology is needed that combines the speed and capability of powered equipment with the portability and low-cost of manual techniques. Such a technology could enable more accessible borewells in regions that suffer from economic water scarcity, including sub-Saharan Africa and parts of South Asia.

38.7.2 Groundwater pumping

The technology set for lifting water is fundamental to groundwater access. An important groundwater pump distinction is based on the source of motive power: human muscles or mechanically powered. Manual-powered pumps are commonly used to lift groundwater from boreholes and shallow wells for household use and low-lift irrigation in rural areas. Technologies for shallow and deep hand pumps were significantly advanced during the International Drinking Water Decade from 1981 to 1990. Robust community-scale pumps, such as the India Mark III and the Afridev, were designed and widely deployed, with attention not only to technical efficiency but also user ergonomics and practical maintenance. The treadle pump, developed in Bangladesh during the 1970s and 1980s, is a low-cost shallow pump that is actuated by strong leg muscles and can lift sufficient water for irrigating smallholder farms. While marginal improvements may be made to manual pump technology, no radical innovations are expected. Rather, water providers can improve access by increasing coverage and ensuring timely maintenance and repairs.

Most groundwater pumps are powered by an external energy source, usually grid electricity or diesel fuel. Efficiency studies of electrical pumpsets in South Asia found average efficiencies of 30% or less (World Bank, 2001; Singh, 2009; Kaur et al., 2016). These efficiency levels are much lower than typical best practice pumpset efficiencies of greater than 50%, and well below the practical efficiency limit of about 85%. Efficiencies can be increased by matching the size of pumps and motors to their tasks, and replacing foot valves and suction and delivery piping to reduce frictional losses. Diesel-powered groundwater pumps are more often used where grid electricity is not available, such as parts of sub-Saharan Africa and South Asia. The cost of diesel necessary to run these pumps is variable and increases the overall operating cost for farmers.

Solar-powered electric pumpsets, which use photovoltaic (PV) arrays to convert sunlight to electricity that then power submersible or surface-mounted electrical pumps, are at an earlier stage of development and deployment. Direct solar pumping can be quite efficient, as all harvested power is used for pumping and there is no need for batteries and associated losses. Modern positive displacement pumps have efficiencies of up to 70% [GIZ (Gesellschaft für Internationale Zusammenarbeit), 2013]. There are significant barriers to the scale-up of PV-powered irrigation pumps, including the high upfront cost of PV systems, which are typically 10 times that of conventional pumps (KPMG, 2014). This cost difference is diminishing over time as PV system costs decline. As there is zero marginal cost for additional water pumping, there is a risk of unrestrained aquifer depletion if the technology is scaled up in the absence of rational water allocation systems.

38.8 Conclusion

The absolute demand for water is increasing due to demographic, industrial, and agricultural growth. Meanwhile, local water resources are constrained, based on precipitation, topology, and geology. The hydraulic boundaries of water basins seldom align with the political boundaries of social discourse, thus water conflicts arise. Groundwater storage is abundant and unutilized in some regions, such as much of sub-Saharan Africa, and overexploited and depleting in others, such as parts of South Asia and North America.

The deployment of select technologies holds promise to enhance the sustainable use of groundwater resources. Groundwater mapping is an essential first step, to understand the subsurface landscape. This knowledge can then be practically applied to manage and increase groundwater recharge, and to reduce saline groundwater intrusion into freshwater aquifers. Improving water-use efficiency in the agriculture, household, and industrial sectors can increase utility from each available unit of groundwater. However, the net groundwater implications of irrigation efficiency improvements are complex, as “wasted” irrigation water often contributes to groundwater recharge. Technologies can be used to improve the quality of groundwater contaminated by salt, arsenic, fluoride, and organic pathogens. Finally, in regions suffering from economic water scarcity, improved technologies for creating wells and pumping groundwater can increase access to needed groundwater.

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