Chapter 2
Options to Increase Freshwater Supplies and Accessibility

2.1 Introduction

Water is the essence of life. Space programs internationally have a focus on finding evidence that at one time water in rivers/streams and oceans existed on the moon, Mars, asteroids, and other planetary orbs. The missions to these space bodies are driven by scientific curiosity, possible economic gain from processes developed in a gravity-free environment, by an evaluation of the practicability of colonization of extraterrestrial neighbors to ease the problems from overpopulation on Earth, and to assess their natural resources. The positive evidence that water has flowed on these space bodies comes from multiple observations and chemical analyses by robotic explorers. There is water on Earth to sustain a growing population if it can be accessed, if it can be kept free of pollution, and if it is allocated and managed so as to be a sustainable resource for human consumption and a necessary support for agricultural and industrial development.

2.2 The Earth's H_2O Inventory: Liquid, Solid, Gas

The growing global population will need access to water to survive and to thrive. Planners must know where the water is and develop concepts of how it can be used most effectively where it is found or where it is moved to service populations with water deficits. Finally, planners must project changes that will take place as a result of global warming/climate change in order to more efficiently use water supplies. This section will discuss how the global stocks of water are stored and the percentages of the total water on Earth each storage phase contains [1]. A later section will consider global warming/climate change as it progresses and alters the amounts of water available at Earth locations and its availability for consumption, agriculture, and industrial/manufacturing needs.

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Oceans and seas contain 96.5 % of the Earth's water. It is not potable without desalinization but in a few locations seawater is piped inland and used to support an integrated project for brine shrimp aquaculture and to grow the vegetable money crop *salicornia* for European consumption [2] oceans, seas, rivers, and lakes yield fish, shellfish, kelp, and algae that are a major food source in for many global populations.

Freshwater comprises the remaining 3.5 % of water on Earth. Of this, about 1.74 % is water locked in icecaps and glaciers. Ground ice and permafrost add another 0.002 % to the inventory. Freshwater from ice is not readily available to populations other than indigenous Arctic groups that melt ice and snow as sources of the commodity. Ice is not easily transportable to where it can be harvested to produce safe water although an iceberg from Antarctica was towed by a sailing ship to Callao, Peru, at the beginning of the twentieth century to provide freshwater for a parched city. Another 0.014 % is in surface waters (freshwater lakes hold 0.007 %, rivers and streams carry 0.0002 %, and swamps have 0.0008 %). Saline lakes and inland seas contain 0.006 % of surface waters.

Subsurface waters include aquifers that contain freshwater or brackish water. Freshwater aquifers store 0.76 % of the Earth's water, 0.34 % in shallow aquifers (less than 750-m deep), and 0.42 % in deep aquifers (greater than 750-m deep). These freshwater aquifers are the important sources of water that sustain humans and the agricultural systems that provide much of our food. Soil moisture holds 0.001 % of the planet's water. Saline (brackish) water aquifers can be used for some cropping (e.g., barley) depending on water salinity and can also be feedstock for desalinization.

The atmosphere contains 0.001 % of the Earth's water. Some villages in India and elsewhere have gone from water deficient to water available for basic needs by extracting water from the atmosphere [3]. Finally, biological systems hold 0.0001 % of the Earth's water.

It is truly astounding to realize that naturally occurring freshwater that sustains most populations worldwide for potable water, for cooking, for personal hygiene, for sanitation, for irrigation and animal husbandry, and for industrial uses, represents only about 0.76 % of the Earth's total water inventory (as liquid, solid, gaseous phases). It is equally mind-boggling to learn that one and a half billion of the more than seven billion people on earth do not have access to safe water and that more than two billion people do not have water to establish sanitation systems to help them develop a healthy living condition. These are problems that do have solutions as will be discussed in a later chapter of this book.

2.3 Volumes of Water for Some Agricultural, Industrial, Commercial, and Domestic Use

Up to 70 % of the water taken from rivers and aquifers is used for agriculture to grow crops and for animal husbandry, our sources of food, whereas 22 % is used by industry and 8 % for domestic and commercial needs. The amount of water used for a given purpose varies significantly from country to country depending on the economic condition, climate, availability and efficiency of water delivery systems, and cost. For example, in the USA, 500,000 gallons of water is necessary to grow one ton of rice, whereas in Australia, the water need is 400,000 gallons, and in India and Brazil, more than one million gallons of water are necessary to grow one ton of rice. Similarly, it takes 225,000 gallons of water to grow one ton of wheat in the USA but takes 182,000 gallons in China and 625,000 gallons in Russia to do the same. The amount of water varies because each country or region has its particular seed species that is sown, climate (temperature, precipitation), hours of exposure to sunlight, topography, and soil type. Table 2.1 presents some general figures of water used in the agricultural, industrial, and domestic/commercial sectors [1, 4].

2.4 Per Capita Water Allowances in 2012 with Recalculations for 2050

There is sufficient freshwater on Earth to sustain the growing global populations. However, the distribution of Earth's water supplies is irregular geographically so that there are nations and regions with water surpluses and nations and regions with water deficits. As cited previously, in 2011, about one billion people on Earth did not have access to safe and sufficient water, and more than two billion persons did not have sufficient water to use for sanitation. Parts of Africa, the Middle East, and Asia suffer from these problems. In some African regions, for example, citizens are subsisting on far less than the 50 L/day basic water requirement (BWR) that has been set by some health organization (e.g., for drinking, cooking, personal hygiene). In developed countries, citizens use far more than the BWR for these and other purposes.

Because of population growth, the deficiencies in water supplies that existed in 2012 will intensify with time as per capita availability of water decreases, sometimes dramatically. This could lead to internal/internecine conflicts or war between nations in an effort to gain access to water especially for drinking and cropping. If there are no changes in projected future fertility rates or in renewable water supplies, the per capita water deficit condition for many countries will change from grave to critical. Table 2.2 presents examples of changes in the water availability condition that will occur in African, Middle Eastern, and Asian countries if additional water supplies are not found or accessed [3, 5–7]. Whether countries have large or small populations or have strong or weak economies, the per capita freshwater accessibility will diminish with time unless strategies are put in place to initially stabilize and subsequently increase water supplies. Some strategies are simple but would require significant investment whereas others are complex and more costly. These are discussed in the following section.

Countries with contracting populations such as Japan and many European nations with sufficient water (e.g., Germany, Italy, Russia, Ukraine) will have an

Table 2.1 Water usage by domestic, agricultural, and industrial sectors for daily living, growing comestibles, and manufacturing goods

Use/product	Water volume (in gallons)
Domestic	
Per capita home use (industrialized nations)	70
Toilet flush	1.5–3
Shower per minute	4–5
Bath	20–30
Wash dishes by hand	9–20
Dishwasher	9–12
Automatic washing machine (front/top load)	24/40
Water lawn 1 h	300
Agriculture sector	
1 ton of rice	480,000
1 ton of wheat	135,000
1 ton of corn	85,000
1 ton of alfalfa	135,000
1 ton of soybeans	160,000
1 ton of sorghum	75,000
1 ton of oats	140,000
1 ton of potatoes	60,000
1 ton of sugar beet	95,000
1 ton of sugar (from cane/beet)	28,100/33,100
1 gallon of milk	2,000
1 hen's egg	400
1 ton of beef	5,000,000 if not recycled
1 ton of cotton	2,500,000
1 barrel of beer (32 gal)	1,500
Industrial sector	
1 ton of finished steel	62,600
1 ton of synthetic rubber	110,000
1 ton of nitrate fertilizer	82,000
1 ton of paper	2,500–6,000
1 ton of fine book paper	184,000
1 ton of bricks	250–500
Refine 1 42 gallon barrel of oil	1,850
Refine 1 gallon of gasoline	63

One gallon = 3.875 L. Water use in the agricultural section is general and does not reflect the range that exists between growing areas because of climate and soil type, orientation, and other conditions [1, 8]

increasing per capita renewable freshwater supply unless a rising birth rate or climate change affects it. In theory, countries with excess water and in a favorable geographic location could export it as an economic commodity to "nearby"

Table 2.2 Growing populations will result in reduced renewable freshwater supplies per capita for most nations if population and fertility projections are met

Country	Actual renewable	Population	Per capita	Population	Per capita
	Water resources km^3	Mid-2011 $\times 10^6$	Water 2011 m^3	Mid-2035 $\times 10^6$	Water 2035 m^3
Grave water stress will intensify					
Algeria	14	36	388	42	328
Burkina Faso	13	17	765	33	391
Burundi	4	10	392	20	201
Egypt	58	83	702	118	490
Israel	2	8	253	10	202
Jordan	1	7	151	9	108
Kenya	30	42	721	60	498
Libya	1	6	156	9	106
Morocco	29	32	898	39	741
Rwanda	5	11	459	20	250
Saudi Arabia	2	28	72	36	56
Tunisia	5	11	467	12	409
Yemen	4	24	168	38	104
Water stress will shift from marginal to grave					
Ethiopia	110	87	1,263	188	586
Nigeria	286	162	1,762	295	968
Somalia	14	10	1,414	17	833
Uganda	66	34	1,913	79	830
Water stress will remain marginal					
India	1,897	1,241	1,528	1,520	1,248
Iran	138	78	1,771	96	1,442
Tanzania	91	46	1,970	59	1,534
Water condition will shift from sufficient to marginal					
Afghanistan	65	32	2,006	50	1,297
Ghana	53	25	2,120	35	1,518
Water will remain sufficient					
China	2,829	1,346	2,101	1,378	2,052

This table gives examples of the degree of these reductions for some countries in Africa, the Middle East, and Asia during a generation from 2011 to 2035. Water stress is grave with <1,000 m^3 per capita, marginal with >1,000–<2,000 m^3 per capita, and water sufficient with >2,000 m^3 per capita [3, 5–7] locations with water deficits. Previous to the political detente, Turkey and Israel had discussions on the tanker transport of water to Israel. During December, 2013, Jordan, Israel, and the Palestinian Authority signed an agreement for the construction of a pipeline that will bring water from the Red Sea to the Dead Sea, construct a desalination plant in Aqaba, Jordan that would supply water as well to Eilat, Israel, while at the same time, Israel would release water from the Sea of Galilee (Lake Kinneret) to the West Bank citizenry.

2.5 Strategies to Improve Water Supplies

Whatever strategies are employed to improve access to renewable freshwater sources for populations inhabiting areas with water deficits will run into a barrier. This is an economics-based benefit/cost analysis of projects being evaluated: costs to build and maintain a system to provide water will exceed benefits in the short term. If such results are adjusted by factoring in social and political benefits, it will become readily apparent these will more than balance economic ones in the long term for existing and growing populations. Projects supported with this as a view toward a realistic future will likely provide the basis for important economic gains for those who supplied investment capital to bring water access strategies to fruition.

2.5.1 Import/Export Freshwater

The world has built tens of thousands of miles of pipelines to move oil and natural gas from their sources to where these fuels are used or loaded onto tankers for delivery to user nations. Investments to build the systems of pipelines were made because they transported high-priced commodities. In 2013, the price of a barrel of oil was in the US$90–100 range. The price of an equivalent amount of water in Washington, DC, with all taxes and extra charges is less than US$1 (US$0.62 a barrel equivalent). This low-value commodity, more precious to human life than oil, has not been an attractive investment for governments or organizations to build pipelines to move freshwater from where it is in excess to areas that have serious water deficiencies. This may be within a country or from one country to another. Thus, in order to supply freshwater to growing populations, a pipeline network to do so is an important strategy. Saudi Arabia has done this by laying more than 4,000 km of water distribution pipelines from Red Sea desalination plants and other freshwater sources to urban centers and industrial complexes. How easy and economically this can be done depends upon the location of a water source and a population or country that needs the water, and a government's economic capability. In the Middle East, for example, Kuwait could pay for a pipeline to bring a water supply from Iraq. If politics can be put aside, the United Arab Emirates and

Saudi Arabia have the economic capability to build pipelines to import water supplies from Iran. In Africa, the economic capability to build pipelines is limited. If international institutions would provide funds to do so, Mali could send water directly to Burkina Faso as could the Democratic Republic of Congo to Rwanda and Burundi. The cost of imported water for consumers should be gauged to local economies and earnings.

Water can also be moved via aqueducts or canals. The problem in transporting water in this way is that a significant volume of the commodity can be lost to evaporation or seepage. Nonetheless, these methods are generally used within a country. This is the case with water brought through a system of canals from the Colorado River to water-deficient Southern California, 300 mi ($\sim$480 km) away, or from Northern California to Southern California, 400 mi ($\sim$640 km) distant. Water can also be carried through tunnels excavated in mountains. This limits water loss by evaporation and/or seepage. New York City receives freshwater from a Catskill Mountains source 90 mi ($\sim$125 km) to the north via a series of tunnels. However, tunnel excavation is very costly. Thus, to maximize the volume of water received at a water poor location, transport by pipeline is preferred especially if the water is to be transported through an arid region as is the case in Saudi Arabia.

2.5.2 Find New Freshwater Sources

2.5.2.1 Aquifers

Hydrogeologists explore for confined aquifers that are not recharged from the surface and unconfined aquifers that will be recharged with freshwater as water is pumped out. Freshwater aquifers are the principal targets. However, brackish water or saline aquifers can be important in the future as stock for a desalinization project or for irrigation of crops that will grow when irrigated with brackish water (e.g., barley, asparagus). Geologists first review the rocks in an area of interest with the aim of finding sedimentary rocks such as sandstones, limestones, or conglomerates, the types that most often contain extractable water supplies. Sedimentary rocks can have porosity (voids between the grains or particles that comprise the rocks and that can store water) and permeability [interconnected voids so that water (or oil) can readily flow through the rocks]. The other two general rock types, igneous and metamorphic rocks, may have voids, fractures, and fissures that can store water and through which water can move but these are much less prevalent as aquifers. Nonetheless, they may be an important source of drinking water and must be evaluated as to their potential as aquifers. Aquifers in igneous rocks in the state of Washington in the USA provide two-thirds of the state's drinking water.

Clues in the exploration for aquifers in an area of geological interest include the presence of springs, seeps, lakes or swamps, growths of water loving trees in arid regions such as cottonwoods and willows, and topography because aquifers will be closer to the surface under valleys than beneath highlands. The geologist can also learn much from records of existing wells in a region that could help locate a new aquifer [e.g., evaluate the depth to aquifer water, the volume that can be pumped so as to maintain a steady water yield (discharge = recharge), and well records that show rocks in the strata down to the aquifer and perhaps deeper].

Once a site for exploration is selected, drilling follows. If an aquifer is found, pumpage tests are made to determine whether there is an exploitable aquifer. If so, tests continue to determine what volume of water can be withdrawn to establish an equilibrium with a recharge volume. If exploitation is indicated, chemical analyses are made on the water to assure that the quality is acceptable for drinking or other uses. An assurance of good water quality leads to exploitation in a sustainable way.

2.5.2.2 The Atmosphere

Humidity in the atmosphere can be extracted to provide additional water for drinking, cooking, and personal hygiene [8]. The process involves first moving the air through filters to remove particles, pollutants, and microorganisms. Next, the air is moved through a desiccant (silica-based gel granules) that absorbs humidity naturally. Then, water desorbs from the desiccant as steam by wind-drying, vacuum, and moderate heating. The steam condenses spontaneously at relatively low temperatures to yield clean water. Cooling speeds up the condensation process and preserves heat energy that is recycled back into the system. Minimal electrical energy is used in the extraction to condensation phases. The Indian company that manufactures water from air extraction equipment can provide additional information on the machine at *watermakerindia.com*.

The system was installed in Jalimudi village, Andhra Pradesh state in the southeastern hinterlands of India, far from pipelines, at a cost of $100,000 with a grant for electricity from the Indian government [9]. The water from air equipment provided 5 m^3 (5,000 L) of clean water daily for 600 villagers to use for drinking, cooking, and personal hygiene. The system is functional and in use in Indian factories, Rural Health Mission hospitals, dental and other offices, and homes. Larger and more costly versions of the equipment can extract up to 1,000 m^3 (1,000,000 L) of clean water daily from the atmosphere depending on the humidity. This can provide the basic water requirement of 50 L per day for 20,000 people. Clearly, the $100,000 water extraction unit could help supply water to the many small villages worldwide that do not have access to clean water or have to walk many kilometers to get water that may not be safe for human consumption. Subsidies to purchase, install, and maintain the extraction units will have to come from governments or international organizations such as the World Bank and regional development banks. In addition to India, these water extraction machines have supplied clean freshwater in the Middle East, at hospitals in Venezuela and Bolivia, where the tap water is contaminated, and to the Chinese Navy, the US Marines, and the South African Army. Other companies as well have constructed machines that extract drinking water from the atmosphere.

Another water extraction from air technique is in prototype evaluation. It operates as part of a wind turbine 34-m high that has produced 62 L an hour in a desert area near Abu Dhabi. First air is sucked into the nose of the turbine and passed through a cooling compressor behind the propellers. This extracts humidity from the air and creates moisture that condenses. Water collects and is purified as it moves through stainless steel pipes into a storage tank in the bottom of the wind turbine. The wind turbine generates the electricity that drives the water extraction operation. The system is claimed to produce 1,000 L a day. At a subsistence need of 5 L daily, the system could serve 200 people, hardly worth the projected cost of between US$660,000 and US$790,000. In addition to the cost as a problem, nature plays a role because a 15-mph wind is necessary to turn the 13-m-diameter propellers in order to generate electricity. More information can be found at www.eolewater.com/gb/our-products/range.html. The water extraction from air machine described in the previous paragraph is, at this time, the more viable method in terms of amount of water produced daily and in terms of the costs involved.

2.5.3 Recycle Wastewater into the Freshwater Inventory

2.5.3.1 Domestic Sewage

Urban populations are growing worldwide as rural dwellers move to cities for employment, education for their children, and better healthcare. In many less developed and developing countries, urban sanitation systems have not been extended to handle the wastes from this added population and the wastes are disposed of in open canals that discharge into rivers or oceans or onto land. This presents a health hazard that must be dealt with. Urban centers that already suffer from water deficits have an added burden on water supplies from an increased population. Both problems can be solved with investment in pipe-based systems that collect the wastes and carry them to a sewage treatment plant. Here, the solids are separated from the liquids. The liquids are treated to remove pathogens, put through a chemical treatment that purifies the waters, and are then ready for distribution through another system of pipes to users either at a series of fountain discharges or at dwellings.

The costs of building a collection–treatment–distribution facility and maintaining it are high but so are the sociopolitical and economic benefits that keep a population healthy without contracting illnesses bought on by poor sanitation. This allows citizens to work at their jobs without losing productivity because of absentee sick days. Although the cost of building and maintaining such a facility is high so are the short- and long-term benefits. As with other investments that increase water supplies, costs for the construction of such facilities must be borne or shared by taxpayers, governments, and by international organizations such as the World Bank, the African Investment Bank, the Inter-American Development Bank, and

US Agency For International Development. Non-Governmental Organizations that have strong financial resources share in sanitation/water availability projects.

2.5.3.2 Wastewater from Commercial Ventures

Domestic and commercial water use combined comprises 8 % of consumable water now used on Earth. The commercial wastewaters originate from many sources such as hotels and resorts, restaurants, office buildings, business parks, large condominiums, and cooperative complexes. Together with these sources, hospitals, schools (K-12) and colleges/universities, government and military facilities, retail sales stores in an out of malls, laundries, and car washes comprise a true a multitude of sources with a myriad of uses for water.

Water to service these needs is drawn from aquifers, from surface waters that likely have gone through a treatment facility before being distributed, or is delivered by water suppliers. Much of the water is used to flush toilets and other sanitation needs as keeping commercial sites clean (e.g., for healthcare), or as in food preparation. However, depending on the climate (e.g., in a warm region), large volumes of water can be used for air-conditioning and in (esthetic) lawn maintenance. For many commercial operations that exist in developed countries, in urban areas of developing countries, and in some population centers in less developed countries, the wastewater flows into a collection facility where it is subjected to treatment before being recycled or released into surface waters. Problems arise when collection and treatment facilities do not exist so that contaminated wastewater is released into open canals that run through populated areas, thereby creating human health hazards along their flow paths into streams, rivers, or oceans.

2.5.3.3 Industrial Wastewater

Of the 22 % of the Earth's freshwater inventory used by industry, about 13 % is used in power generation and about 9 % for all other industrial ventures. About 59 % of the 22 % freshwater supply is used in high-income countries whereas only about 8 % of this supply is used in low-income countries although this latter figure is increasing markedly. Most industries supply their own water, mainly from surface sources with the rest from groundwater. Others purchase it from city water supplies (wells, collection–treatment plants). Lack of a reliable supply of useable water constrains industrial development. The demand for more water by industry is rising because of a growing demand for consumer products in developing and less developed nations and because of the increased number of factories in these countries. This latter increase is driven by two forces. One is internal investment and development as a national plan. The second is investment by industries from developed nations moving factories to low-income countries as the result of one or a combination of factors. The most important factor is the availability of reliable water and electricity supplies. Without this, there would be constraints on industrial development. Others include government incentives (e.g., tax relief), an educated and trained labor pool, lower labor costs and less union influence, and less stringent environmental restrictions for the treatment and discharge of wastewater. The relocation of industrial ventures to low-income countries is often close to urban centers. If wastewater from factories in or close to these centers is not collected, treated, and recycled, but is simply discharged into the immediate or nearby environments, it will likely harm people and damage ecosystems.

Major industrial uses of water are for the production of food, chemicals, paper and paper products, primary metals, and gasoline, and oils. The water is used for product fabrication and may be incorporated into the products. It is used for processing, washing, diluting, and cooling during industrial operations, and for transport of products. Industrial facilities with a small number of employees or large ones with 100s or 1,000s of employees use water for drinking and for washing and flushing. Industrial contamination of water compared with pollutants from other sources (e.g., domestic, commercial, agricultural) is generally more toxic (e.g., with organic and inorganic chemicals including heavy metals, toxic sludge and solvents), more concentrated, harder to treat to remove the toxins, and longer lasting when insufficiently treated wastewater invades an environment.

The amount of industrial wastewater that is collected, treated, and recycled is calculated to be 30 % of the total [10]. The other 70 %, estimated at 300–-500 million tons of untreated industrial waste, are released onto land where they may pollute soils and/or infiltrate through soil and rock to pollute aquifers, or flow into streams, rivers, and oceans where they may damage ecosystems that otherwise support life and are productive. Collection and treatment of industrial wastewater to a quality that can be recycled into a source industry process will help sustain a water supply by decreasing water withdrawal needs. Japanese industries recycle 90 % of their wastewater and find that higher productivity and increased profits are associated with greater reuse of treated wastewater. The industrial discharge of treated wastewater is essential to keep ecosystems healthy and productive for humans and other living things.

The quality of water needed for different industrial processes varies so that wastewater treatment is tailored to an industry's requirements. For example, pharmaceutical and high-tech (e.g., computer components manufacturing) industries require very high-quality water as does food processing. Industries that are able to use a lesser quality water have lesser treatment expenses to recycle and reclaim their wastewaters unless they intend to release it into the environment. It is a long-term financial investment to build the infrastructure to manage the collection and treatment of industrial wastewaters and the redistribution of clean freshwater. However, as already noted, the long-term benefits will equal or likely exceed the cost with improved profits for investors. Thus, each industry requires its own specific treatment to generate the quality of water it needs to function or to discharge clean freshwater offsite. Technology advances in treatment protocols will reduce costs and bring down barriers to the use of collection, treatment, and recycling of wastewater to yield toxin-free water or allow its discharge into ecosystems.

There is no question that industry can use water in a sustainable manner and maintain a high level of productivity. Industrial development can take place without harming the environment and diminishing productivity. The keys to achieve this result are the management of water supplies with the goal of decreasing the volume of water withdrawal and by supporting research that generates innovations in wastewater treatment to quality levels necessary to an industry or for discharge into the environment. The implementation of an installation and use of these innovations as they are tested and proven reliable will yield cleaner processes, better products, and lead to a greater degree of sustainability. This management of water supplies and the drive to a greater degree of recycling is basic to the ability to adapt to times of water scarcity that are projected to be more pronounced in many areas (e.g., Africa, Australia, South America) as global warming causes changes in water supplies.

The principal competition for existing freshwater supplies is from the agricultural sector, and this will have to increase in the future for two main reasons. The first is population growth and the need to grow more crops to feed more people (1.4 billion more by 2035 and an additional more than a billion people by 2050). The second is that more grain and fodder will be needed to feed livestock because there are more people with disposable income in developing countries (e.g., China) and to some degree less developed countries that are altering their diets to include more protein (e.g., meats) similar to populations in developed countries. Much of this dietary change is the result of more populous middle classes that travelled abroad and experienced diverse foods they enjoyed but with which they had not been familiar. The change is also stimulated by media exposure especially via television and Internet sites that have a constant flow of food-related propaganda. The problems of reclaiming and recycling of wastewater from agricultural production are discussed in the following section.

2.5.3.4 Agricultural Wastewater

As noted at the beginning of this section, 70 % of freshwater resources are used in the agricultural sector, mainly for irrigation where rain fed agriculture is not reliable for cropping because of a variable climate. Irrigated fields are most important because the 20 % of the world's agricultural land now farmed using irrigation produces 40 % of the global crop output. Large amounts of water are used as well in livestock production for drinking, cooling, and cleaning. The volume of water used in livestock farming is increasing greatly as the demand for livestock products (especially beef) rises with an improving economic status of a growing middle class of citizens in developing and less developed nations. Questions we deal with here are where in the agricultural sector, is it possible to reclaim wastewater and how much of this water can be economically reclaimed and reused? If not reclaimed, what then? We are also concerned with minimizing drainage of wastewater that flows overland and contains or incorporates nutrient (e.g., potassium K, nitrogen N, phosphorus P) or toxins (e.g., arsenic As, pathogens). These can infiltrate aquifers or discharge into fresh, brackish, and saline surface waters, disrupting the health condition and productivity of ecosystems they feed. Finally, there is the problem of treating water that contains wastes generated by aquaculture and recirculating it into manufactured fish farm aquaria.

Waters used in irrigation reenter the hydrological cycle and are naturally "scrubbed" as they recycle into aquifers and surface waters for reuse. As populations continue to grow, the mass of food that will have to be produced will rise dramatically. Estimates are that by 2050, food production will have to increase by 70 % (or more, author's determination) to feed the estimated additional 2.5 billion or more people added to the 2013 global population that today has one in seven people on Earth suffering from malnutrition because of the lack of access to enough and good quality food [11]. For this reason, more water will be needed by the agricultural sector even as hybridization and/or genetic engineering develop seeds for crops that require less water to grow or that improve their drought resistance. For rain fed cropping, this means developing the capability to store captured rainfall in reservoirs (that can lose a great volume of water to evaporation) or in underground caverns as backups to irrigate rainwater-starved crops.

Human-directed recycling in the agricultural sector has relatively few and somewhat localized or regionally important targets unlike targets for the recycling of industrial waters. The agricultural targets are associated with livestock production, slaughter, and preparation of products. This could be considered agri-industrial that perhaps could just as well have been discussed previously in the industrial section.

The larger targets for reclamation and recycling of wastewaters include cattle feedlots containing thousands of cattle. The Simplot feedlot outside of Grandview, Idaho, USA, has a capacity for 150,000 cattle. The USA had 10.5 million head of cattle cycling through feedlots in 2010. Commercial chicken farms for meat or eggs (some with tens of thousands and up to a million chickens) present sites for recycling of wastewater. Smaller but no less important areas for collecting wastewater, treating them, and reusing the clean water include slaughter houses, meatpacking plants, especially those that have to process 500,000 head of cattle annually to be profitable, and chicken-processing plants. Intensive farming of pigs, ducks, turkey, and geese add to the draw on freshwater. These animal husbandry sites are focused for reclamation of wastewater. Aquaculture farms are also locations where water can be cleaned and recycled perhaps following fish tank water reclamation methodology. Other candidates for water collection, treatment, and reuse are farms with dairy cattle. Factories that process fish from marine and saline or freshwater catches are also sites where wastewater can be captured, treated, and reclaimed. Recycling in all these cases will reduce withdrawal of freshwater from aquifers and surface waters, thereby improving water supplies. Treating wastewater will help secure the cleanliness of surface waters and aquifers.

Cattle feedlots in the USA are categorized as small when they contain less than 1,000 head of cattle, as medium-capacity lots when the number of cattle is more than 1,000 but less than 31,999, and of large capacity when they feed more than 32,000 head of cattle. A feedlot in Broken Bow, Nebraska, contains 85,000–90,000 cattle. Smaller feedlots comprise 95 % of those in the USA but 80–90 % of the fed cattle are in the larger feedlots. Cattle are generally brought from grazing land to feedlots where they are confined for 4–5 months until their weights increase from 600–800 lbs (273–364 kg) to 1,000–1,250 lbs (455–545 kg), and they are ready for the slaughterhouse. The amounts of waste that is produced are great. Each head of cattle in feedlots creates more than 15 times the waste daily that a human produces. Thus, a lot with 10,000 head of cattle originates the same amount of waste as a city with 150,000 inhabitants, and the Nebraska feedlot with 85,000 cattle produces wastes equal to that produced by a metropolis of about 1–1/4 million inhabitants. Feedlot wastes have been found in surface waters in watersheds far from a point source and in aquifers.

In this section, we are dealing with water that cattle drink, water used to cool and clean feedlot stock, and urine, and whether these fluids can be recycled as water cattle can safely drink. The discussion on cattle that follows applies as well to commercial farming of pigs. Cattle are penned in at feedlots that are constructed so that urine and other wastewater will runoff into collection/catch drains through a system that allows sediments to deposit. It then flows into retention ponds for treatment. This prevents pollution of streams, rivers, and lakes by nutrient-rich (potassium, phosphorus, nitrogen) wastewater. The holding ponds should be located away from recharge areas for unconfined aquifers. To prevent pollution of aquifers, the holding ponds should be constructed with impermeable liners such as clay or bioresistant plastic. In addition, the lined ponds must have secondary low areas, also lined, to catch and retain any overflow from the ponds during an extreme weather event without endangering adjacent land surfaces, aquifers, streams, rivers, or lakes. If a management system is in place to move feedlot wastewater from the collection sites (the holding ponds) to treatment plants, the cleansed water can be recycled for feedlot reuse and reduce the need to withdraw much additional groundwater or surface water. Water management systems have had some success but in the USA, for example, drainage from all livestock into freshwater resources still accounts for 33 % of phosphorus and 32 % of nitrogen loading, 37 % of pesticide loading, and for 50 % of the influx of antibiotics into catch basin waters [12].

Meat-packing plants are sources of wastewater and cattle body fluids that can contaminate aquifers and surface waters if they are not collected and treated to remove contaminants before reusing the water and fluids or discharging them into the environment. This problem is serious worldwide. For example, estimates for 2013 have the US plants producing 11 million tons of beef annually with Brazil, the European Union, and China, having annual productions of 9.9, 7.8, and 5.8 million metric tons of beef, respectively [13]. These figures represents about a 60 % increase during the first decade of this century. Cleanliness at these cattle processing facilities and the treatment of the waters or fluids they discharge to remove inorganic and organic pollutants is essential lest there be public health problems that affect societies and environments.

In 2009, there were an estimated 50-billion chickens (plus ducks, turkeys, and geese) in commercial factory farms worldwide, 9 billion in the USA, 7+ billion in China, and 6 billion in the European Union. [14]. Brazil and Indonesia also had high poultry populations. The emission of urine and its capture and treatment for recycling clean water is not a problem for commercial poultry factory farms because birds (poultry) do not have urinary bladders and hence do not issue urine. The urine from the poultry kidneys is continually added to digested feed that results in the dehydration and precipitation of uric acid precipitates. This is the white matter that comprises poultry droppings. The water that can be reclaimed and recycled for chicken raising is the water used to clean chicken pens after each 5–6-week growth period when the chickens reach the target 3–3½ lb weight (~ 1.5 kg) before they are slaughtered and dressed for sale. This water contains nutrients, antibiotics, pesticides (some with arsenic), vaccines, and other chemicals used to keep the poultry healthy and growing, in addition to cleaning compounds that are used. These waters must be collected and treated to remove contaminants before they recycle into a poultry farm or are discharged onto terrain or into surface water bodies. Failure to do so will pollute soils, aquifers, rivers, streams, and lakes. Similarly, water used to wash and clean chickens during the dressing stage and water used to clean the dressing areas carry these same contaminants and has to be captured and treated in the same way before recycling or discharge. What applies to commercial chicken farming applies as well to commercial duck, turkey, and geese farming.

Chickens in commercial egg-producing farms present the same water contamination problems and solutions as those used at chicken farms to produce meat. One farm in California, USA, has more than 800,000 laying hens. These require about 320,000 L (~ 80,000 gallons) of water daily for the hens. Reclamation of the water used in cleaning the hen houses can be recycled into the farm water supply. Different phases of chicken farming (in the tropics) whether for meat or eggs, and of the farm as a commercial enterprise have been published by Agromisa, a Netherlands firm [15, 16].

2.5.4 *Create/Extend Freshwater*

2.5.4.1 Desalination

Nations with marine coastal zones and a deficit in freshwater supplies can generate freshwater by desalination of seawater. However, desalination is an energy consuming, hence an expensive process, but one that can provide a reliable supply of freshwater. Saudi Arabia is an oil-rich state in a water poor region. The country generates about 50 % of its municipal freshwater needs and 70 % of its drinking water requirements by desalination of Red Seawater using its oil to generate the energy needed by its desalination plants.

There are about 15,000 desalination plants worldwide that provide freshwater to areas that have natural water deficits. Another 120 are in a planning or construction phase. Most draw their feed water from oceans/seas. The biggest desalination facilities are in the Middle East in Saudi Arabia, the United Arab Emirates, and Israel. The Raz Azzour and the Shoaiba 3 plants in Saudi Arabia produce over one million m^3 daily while the Ashkelon plant in Israel produces close to a half a million m^3 daily. The largest inland facility in El Paso, Texas, USA, uses brackish groundwater as the feedstock for desalination and produces 105,000 m^3 daily. Most desalination plants produce less than 5,000 m^3 daily. The 2010 production of freshwater from desalination was more than 68 million m^3 and is projected to grow to 120 million m^3 by about 2020 although this figure may be too high as funding slowed because of the global recession in 2008.

More than 85 % of desalination plants use either multistage flash distillation or reverse osmosis. Three quarters of these are in the Middle East. The Raz Azzour and the Shoaiba 3 plants cited above use the multistage flash process while the Ashkelon plant uses reverse osmosis. Reverse osmosis uses less energy than thermal distillation and is less expensive. It is the fastest growing distillation technique. About half of the existing desalination plants use reverse osmosis. Desalination plants using either method bring the 3.5 % salt content of seawater (higher for the Red Sea or Mediterranean Sea) down to 0.05 %. The output volume of freshwater is about 60 % of the seawater input. This means that the brine issuing forth from desalination processes has a high salt content and poses a waste disposal problem that will be discussed at the end of this section.

The multiflash stage distillation technique uses seawater as the feedstock at pressures less than atmospheric pressure so that the seawater boils at less than 160 °F. At this temperature, scaling (buildup of foulant salts) in the equipment is greatly reduced. The system is designed so that the seawater passes through progressively lower pressure conditions and steam flashes off at steadily decreasing boiling temperatures and is captured. This technique is energy intensive. It is used in most plants in oil-producing countries in the Middle East (e.g., Raz Azzour and Shoaiba 3 cited above) because the oil is available at a much lower cost than would be the case in non-oil-producing areas.

For the reverse osmosis method, seawater (or wastewater from domestic, commercial, industrial/manufacturing sources) is pressure driven through semi-permeable membranes that are manufactured from polymers of polyamide plastics. These separate salts from water. The pressure ranges from 800 to 1,200 PSI (pounds per square inch) for seawater and from 250 to 400 PSI for brackish water depending on the specification of the membranes used. The membranes are tailored specific to the characteristics of the seawater or wastewater feed such as salinity, contained particles, chemicals, and organic contents. In some plants, dissolved matter is separated from the water by sequential passes through membranes with decreasing size characteristics. This and a final purification pass through nanofilters that can remove bacteria, viruses, pesticides, and herbicides and give the desired freshwater product.

An innovative large-scale desalination facility that is projected to provide up to 30,000 m^3 daily is being built in Al-Khafji, Saudi Arabia, a city of 100,000 inhabitants. The plant will use renewable solar energy as its power source [17]. Solar power will become increasingly important in Saudi Arabia where there is an average of 7–11 h of sunshine daily, an average temperature of 25.3 °C, a monthly range of 19 °C, and a high of 45 °C. The solar energy electricity will be generated by IBM-developed ultra-high concentrator photovoltaic cells (a lens focuses the sun's rays on the cells) to drive its seawater desalination operation and a new water filtration technology (specially designed membranes) in its reverse osmosis process. In a second phase, the plans are to ramp up the freshwater production to 100,000 m^3 per day. Electricity storage capability and/or backup electricity generating systems, likely fueled by natural gas, have to be in place to keep the plant functioning during days when there is no sun to power the photovoltaic cells. Saudi Arabia is using about 1.5 million barrels of oil a day to power the government run 30 desalination plants. Though the real cost of supplying oil to the desalination plants from the Saudi fields is very much less than the world price per barrel, the amount still represents an economic burden. By taking advantage of solar power and advanced filtration techniques in new installations, and by retrofitting existing plants to function as hybrids, desalination costs to provide more than 50 % of the country's municipal water supply and 70 % of its drinking water requirements can be reduced significantly [18].

Electrodialysis is one of the earlier methods to produce freshwater from saline waters. It is a membrane technique in which an electrical voltage is used to drive dissolved salts through a series of alternating charge-selective membranes that allow either positive or negative charged ions to pass through leaving a less saline water as a product. An anion-selective and a cation-selective membrane are coupled to make a cell. The cells are grouped in threes with the two outer cells passing the brine or seawater solution with the central cell carrying the dilute solution or freshwater. Several hundreds of cells may be stacked together to form an electrodialysis desalination system. The equipment had a problem with scaling. This was overcome in a reengineered electrodialysis reversal system that flushes scales and other contaminants off the membranes by adding a self-cleaning phase during which the polarity of the voltage is reversed several times an hour. The electrodialysis reversal unit results in higher recovery and longer membrane life.

Freshwater is also being generated in relatively small volumes to serve personnel on nuclear-powered naval vessels and at nuclear power facilities by using excess heat to drive the thermal distillation process (e.g., in Russia, in South Africa, and in Japan until the 2011, tsunami caused a nuclear plant accident and the subsequent shut down of all Japanese nuclear power facilities).

The brine wastewater discharge from desalination plants presents a special challenge because of the concentrated salts content ($\sim$8.6 %) that represents 86 kg (189 lbs) per metric ton of wastewater. Added to this is the problem of the chemicals used in descaling matter deposited during desalination, and the temperature of the wastewater. Can it be used? Can it be released directly into the environment from which it was taken? If so, why? If not, why not? Can the brine itself be recycled for use in another sector? One possibility depends on the industrial infrastructure at sites not too distant from a desalination plant. The brine outflow can be directed to drying ponds and the dried salts can be sold to a chemical industry that can process them to extract chemical elements and compounds that can be sold to for industrial/manufacturing use. These could include purified salt ($NaCl$) as condiment, salts to melts snow/ice, potassium (K) for use in fertilizer, or bromine (Br) for pharmaceuticals. Disposal of the chemical residue has to be controlled and enforced by environmental regulations.

Impacts of desalination plant discharges on the marine environment have been reviewed critically [19]. Researchers emphasize that a desalination plant brine outflow, warm and with a salinity at ∼8.6 % should best be cooled, diluted (e.g., with seawater), and only then released into the ocean. It can also be discharged, cooled, but without dilution directly into the marine environment with outfalls a good distance away from unique, biologically diverse coastal ecosystems. Closer to such environments, the discharge can affect life forms in the intruded ecosystems to a greater or lesser degree depending on the wave, tidal, and current activity at the discharge zone. High-energy turbulent coasts with continual flushing will suffer less environmental impacts, and these may be within tens of meters of the discharge outfall. In older multiflash stage plants, some outfalls were in quiet coastal environments. These underwent widespread alterations to community structure in sea grass, coral reef, and soft sediment ecosystems. Discharge that has minimum effects on marine ecosystems would be in areas 100 s of meters offshore. In all cases, before–after control monitoring of the discharge outfall zones ecosystems is an absolute necessity.

An excellent review of the technology, political, economic, and social factors involved with desalination was published by the US National Research Council [20].

2.5.4.2 Nanofiltration of Tainted River Water

The French water authority designated Vivendi/Generale des Eaux to work with The Dow Chemical Co. to develop a membrane tailored to remove pesticides, herbicides, bacteria, and viruses from the Val d'Oise River water, yet leave in place dissolved minerals important to human nutrition and thus convert the tainted water to potable water [21]. Traditional purification methods did not work on the Oise River water. The area needed a new source of potable water to reduce the withdrawal of groundwater that was lowering the aquifer water table and resulting in land subsidence. The NF200 membrane was developed to remove molecules in the 0.001-μm-size range (1/10,000th of the thickness of human hair) and with a molecular weight of 200. This nanofilter does not remove heavy metals [22]. Two problems engineers had to solve was fouling by biological matter of microbial origin at the nanofilter surfaces and scaling by inorganic foulants. They did this by incorporating an automated system into the process that used anti-scalants and other cleaning agents.

A pilot study to provide clean, safe water to 5,000 people living near the river was carried out and was successful [23]. The nanofiltration system was ramped up and by 2011, 9120 of the specially designed and built membranes were installed at the Mery-sur-Oise water treatment plant. Here, the polluted water is decanted and chemically treated for a few days to allow sedimentation of solids and precipitates. The water is then subjected to ozonization followed by filtration through sand and lastly through charcoal to further cleanse it. In a final stage, the water is (low) pressure driven at 8–15 bars through spiraling tubes of the NF200 nanofilters that present more than three million ft^2 (278,709 m^2) of filter surface. This system is supplying about 140,000 m^3 (37 million gallons per day) of potable water to about 500,000 people (~300,000 households) located just north of Paris. Capital investment for this plant was less than 200,000 euros. The cost of production is about 0.10 € (US$0.13) more than that of a conventional treatment plant. Nanofiltration to cleanse contaminated river water where traditional water treatment is not effective requires that the nanofilters be designed and manufactured according to the physical, chemical, and biological characteristics of the river (feed) water.

2.5.4.3 Reduction of Water Use for Specific Operations

In addition to recycling of reclaimed freshwater from the various sources discussed in this section, a reduction in the use of freshwater can improve the per capita allowance of freshwater for stressed populations as their numbers grow. Drip irrigation targeted to individual plants in a field with the amount of water necessary for optimum growth is one method in use by many agriculturalists in water-stressed regions. This reduces the volume of irrigated water delivered by other methods. By using less water to produce crops that have excellent yields and nutritional value, agriculturalists benefit economically by lowering water supply costs. The use of (DNA) marker-assisted selection (MAS) to produce seeds, following natural hybridization methods that can grow basic food crops with less irrigation water input has also reduced water needs. For example, in the 1970s, one million gallons of water were used to grow one ton of rice. By the end of the century, this had been reduced to less than 500,000 gallons. As noted previously, Australian rice cropping is most efficient and uses less than 300,000 gallons of water to grow one ton of rice. Clearly, there is a range of water use for the same crop yields that exists from growing area to growing area because of climate and soil type conditions. In addition to traditional hybridization, marker-assisted or not, genetic engineering or manipulation of traits from one species to a different species aims to reduce water needs while maintaining or improving crop yields and nutritional values. However, genetically modified organisms are not accepted by countries in the European Union and others outside the Union (mainly in Africa) so that water use to grow a crop may not be reduced there. As noted earlier in this chapter, the agricultural sector uses 70 % of the Earth's freshwater. It is the agricultural sector that has the best potential to reduce the volume of freshwater it uses, thus making more available to expanding populations.

2.6 Benefits/Costs of Improved Water Supply

The costs of improving a freshwater supply vary greatly. For example, generating freshwater from seawater, brackish groundwater, and wastewater depends on the volume of water to be processed (or how much output is planned for), location with respect to the feed water (e.g., depth to aquifer for brackish water), the quality of the water to be delivered, and where clean water is to be sent. Expenditures include the capital cost of the construction of the processing installation and infrastructure, and the operating and maintenance costs. These vary greatly for whichever system is used to produce clean water. For example, the capital cost for a desalination plant and infrastructure can be as little as US$115 million for a small installation or as much as US$1.6 billion (the cost of the first-phase Shoaiba plant and subsequent upgrade in Saudi Arabia). Operating and maintenance costs range from US$2–$11 per 3.75 m^3 of water. The Shoaiba plant produces over 473,000 m^3 daily. The Kwinawa plant in Perth, Australia, had a capital cost of A$387 million and yearly operating and maintenance costs of A$24 million to produce more than 120,000 m^3 per day. Benefits of more water that is accessible to more people are great if it keeps them alive and healthy, able to work and contribute to the well being of a family and a nation in a socially stable society with human, civil, property, religious, and political rights. In the long term, these benefits on which we may not be able to put a monetary value will exceed the costs of making freshwater available for people, agricultural endeavors, and industrial and manufacturing projects. Without the benefits of systems that provide safe water to growing populations, socioeconomic expenses will be enormous because of the economic and political problems that will develop, diseases that will punish societies, and the conflicts and wars that will surely ensue to control water rights.

2.6.1 Support Research

Continued research on how to conserve water, more efficiently recycles water in industrial, manufacturing, and farming operations, collect and treat contaminated water, distribute clean water, and create freshwater that has to be supported by international organizations and governments. Researchers have to evaluate the influence of global warming/climate change on the hydrological cycle and changes in water supplies between regions. This will provide governments the basis on which to plan adaptation strategies that will temper the evolving effects of shortfalls in water supplies for populations and the ecosystems that sustain them through all sectors that support societies and their quality of life.

2.7 Afterword

Water is a principle factor in sustaining a reliable food supply for global citizenry. With this factor positive, we can examine what can be done to increase the world's food stocks to be able to feed a growing global population that is projected to put 2.6 billion more people on Earth in less than two generations by the year 2050. This is largely a subject that agronomists and plant scientists have to solve not only for today but for a future that will bring about more changes in climate than we observe and measure at the beginning of the second decade of the twenty-first century. National and international social, political, and economic decisions must be decided with this in mind. The next chapter will discuss how today's agriculturists can increase global food supplies and how governments must agree to free movement of food from where it is grown or stored to where it is needed to provide for people in regions with food deficits.

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