Water Resources, Agriculture and the Environment

By David Pimentel*, Bonnie Berger#, David Filiberto, Michelle Newton, Benjamin Wolfe, Elizabeth Karabinakis, Steven Clark, Elaine Poon, Elizabeth Abbett, and Sudha Nandagopal

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*College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, USA
Students, Environmental Policy Course, Cornell University, Ithaca, NY, USA

Abstract

Critical need exists to implement water conservation practices in agriculture and to control water pollution. Agriculture consumes 80% of U.S. freshwater resources.

WATER RESOURCES, AGRICULTURE, AND THE ENVIRONMENT

INTRODUCTION

Water is essential for maintaining an adequate food supply and a quality environment for the human population, plants, animals, and microbes on the earth. Per capita food supplies (cereal grains) have been decreasing for nearly 20 years (declined 17%), in part because of shortages of freshwater, cropland, and the concurrent increase in human numbers (FAO 1961-2002). Shortages in food supplies have in part contributed to more than 3 billion malnourished people in the world (WHO 2004a). Two of the most serious malnutrition problems include iron deficiency affecting 2 billion people and protein/calorie deficiencies affecting nearly 800 million people (WHO 2002; WHO 2004b). The iron deficiency and protein/calorie deficiency each result in about 0.8 million deaths each year (WHO 2002). Humans obtain all their nutrients from crops and livestock and these nutrient sources require water, land, and energy for production (Pimentel and Pimentel 2003).

Consider that the world population currently numbers 6.3 billion with over a quarter million people added each day (PRB 2003). The UN (2001) estimates that approximately 9.4 billion people will be present by 2050. In addition, freshwater demand worldwide has been increasing exponentially as population and economies grow

(Hinrichsen et al. 1998; Postel, 1999; Rosencrant, et al., 2002; Shiklomanov and Rodda 2003; UNEP 2003; Gleick 2004). Population growth, accompanied by increased water use, will not only severely reduce water availability per person, but stress all biodiversity in the entire global ecosystem (Vorosmarty et al., 2000).

Major factors influence water availability including rainfall, temperature, evaporation rates, soil quality, vegetation type, as well as water runoff. Furthermore, serious difficulties already exist in fairly allocating the world’s freshwater resources between and within countries. These conflicts are escalating among new industrial, agricultural, and urban sectors. Overall, water shortages severely reduce biodiversity in both aquatic and terrestrial ecosystems, while water pollution facilitates the spread of serious human diseases and diminishes water quality (Postel et al., 1996; Pimentel et al., 1997).

In this article, water utilization by individuals and especially agricultural systems is analyzed. Interrelationships exist among population growth, water use and distribution, the status of biodiversity, the natural environment, plus the impacts of water borne human diseases are reported.

WATER RESOURCES

Hydrologic Cycle

Of the estimated 1.4 x 10^{18} m^3 of water on the Earth, more than 97% is in the oceans (Shiklomanov and Rodda, 2003). Approximately 35 x 10^{15} m^3 of the Earth’s water is freshwater, of which about 0.3% is held in rivers, lakes, and reservoirs (Shiklomanov and Rodda, 2003). The remainder of freshwater is stored in glaciers, permanent snow, and groundwater aquifers. The earth's atmosphere contains about 13 x 10^{12} m^3 of water, and is the source of all the rain that falls on earth (Shiklomanov and Rodda, 2003). Yearly, about 151,000 quads (quad = 10^{15} BTU) of solar energy cause evaporation and move about 577 x 10^{12} m^3 of water from the earth's surface into the atmosphere. Of this evaporation, 86% is from oceans (Shiklomanov, 1993). Although only 14% of the water evaporation is from land, about 20% (115 x 10^{12} m^3 per year) of the world's precipitation falls on land with the surplus water returning to the oceans via rivers (Shiklomanov, 1993). Thus, each year solar energy transfers a significant portion of water from oceans to land areas. This aspect of the hydrologic cycle is vital not only to agriculture but also to human life and natural ecosystems (Jackson et al., 2001).

Availability of Water

Although water is considered a renewable resource because it depends on rainfall, its availability is finite in terms of the amount available per unit time in any one region. The average precipitation for most continents is about 700 mm/yr (7 million liters/ha/yr), but varies among and within them (Shiklomanov and Rodda, 2003). In general, a nation is considered water scarce when the availability of water drops below 1,000,000 liters/capita/yr (Engleman and Le Roy, 1993) (Table 1). Thus Africa, despite having an average of 640 mm/yr of rainfall, is relatively arid since its high temperatures and winds that foster rapid evaporation (Vorosmarty et al., 2001; Ashton, 2002).

Regions that receive low rainfall (less than 500 mm/yr), experience serious water shortages and inadequate crop yields. For example, 9 of the 14 Middle Eastern countries (including Egypt, Jordan, Israel, Syria, Iraq, Iran, and Saudi Arabia) have insufficient rainfall (Myers and Kent, 2001, UNEP, 2003a) (Table 1).

Substantial withdrawals from lakes, rivers, groundwater, and reservoirs used to meet the needs of individuals, cities, farms, and industries already stresses the availability of water in some parts of the U.S. (Alley et al., 1999). When managing water resources, the total agricultural, societal, and environmental system must be considered. Legislation is sometimes required to ensure a fair allocation of water. For example, laws determine the amount of water that must be left in the Pecos River in New Mexico to ensure sufficient water flows into Texas (Washington State Library, 2002).

Groundwater Resources

Approximately 30% (11 x 10^{15} m^{3}) of all freshwater on Earth is stored as groundwater. The amount of water held as groundwater is more than 100 times the amount collected in rivers and lakes (Shiklomanov and Rodda, 2003). Most groundwater has accumulated over millions of years in vast aquifers located below the surface of the earth. Aquifers are replenished slowly by rainfall, with an average recharge rate that ranges from 0.1% to 3% per year (Covich, 1993; La Salle et al., 2001). Assuming an average of 1% recharge rate, only 110 x 10^{12} m^{3} of water per year are available for sustainable use worldwide. At present, world groundwater aquifers provide approximately 23% of all water used throughout the world (USGS, 2003a). Irrigation for U.S. agriculture relies heavily upon groundwater, with 65% of irrigation water being pumped from aquifers (McCray, 2001).

Population growth, increased irrigated agriculture, and other water uses are mining groundwater resources. Specifically, the uncontrolled rate of water withdrawal from aquifers is significantly faster than the natural rate of recharge, causing water tables to fall by more than 30 m in some U.S. regions (Brown, 2002). The overdraft of global groundwater is estimated to be about 200 x 10^{9} m^{3} or nearly twice the average recharge rate (International Water Management Institute, 2001).

For example, the capacity of the U.S. Ogallala aquifer, which underlies parts of Nebraska, S. Dakota, Colorado, Kansas, Oklahoma, New Mexico, and Texas, has decreased 33% since about 1950 (Opie, 2000). Withdrawal from the Ogalla is 3 times faster than its recharge rate (Gleick, et al., 2002). Aquifers are being withdrawn more than 10 times faster than the recharge rate aquifers in parts of Arizona (Gleick et al., 2002).

Similar problems exist throughout the world. For example, in the agriculturally productive Chenaran Plain in northeastern Iran, the water table has been declining by 2.8 m/year since the late 1990s (Brown, 2002). Withdrawal in Guanajuato, Mexico, have caused the water table to fall by as much as 3.3 m per year (Brown, 2002). The rapid depletion of groundwater poses a serious threat to water supplies in world agricultural regions especially for irrigation. Furthermore, when aquifers are mined, the surface soil area is prone to collapse, resulting in an aquifer that cannot be refilled (Youngquist, 1997; Glennon, 2002).

Stored Water resources

In the U.S., many dams were built during the early 20th century in arid regions in an effort to increase the available quantities of water. Although the era of constructing large dams and associated conveyance systems to meet water demand has slowed down in the U.S. (Coles, 2000), dam construction continues in many developing countries worldwide.

Given that the expected life of a dam is 50 years, 85% of U.S. dams will be more than 50 years old by 2020 (ACC, 1999). Prospects for the construction of new dams in the

U.S. do not appear encouraging. Over time, the capacity of all dams is reduced as silt accumulates behind them. Estimates are that 1% of the storage capacity of the world's dams is lost due to silt each year (Economist, 1992).

WATER USE

Water from different resources is withdrawn both for use and consumption in diverse human activities. The term use refers to all human activities for which some of the withdrawn water is returned for reuse, e.g., cooking water, wash water, and waste water. In contrast, consumption means that the withdrawn water is non-recoverable. For example, evapotranspiration of water from plants is released into the atmosphere and is considered non-recoverable.

Human Water Use

The water content of living organisms ranges from 60% to 95%; humans are about 60% water (Tesoro, 2002). To sustain health, humans should drink from 1.5 to 2.5 liters of water/person/day (NAS, 1968). In addition to drinking water, Americans use about 400 liters water/person/day for cooking, washing, disposing of wastes, and other personal uses (USBC, 2001). Compare this amount to the 83 other countries that report an average below 100 liters/person/day of water for personal use (Gleick et al., 2002).

Currently the U.S. freshwater withdrawals, including that from irrigation, total about 1,600 billion liters/day or about 5,700 liters of water/person/day. Of this amount about 80% comes from surface water and 20% is withdrawn from groundwater resources (USBC, 2001). Worldwide, the average withdrawal is 1,970 liters/person/day for all purposes (Gleick et al., 2002). Approximately 70% of the water withdrawn is consumed and is non-recoverable worldwide.

AGRICULTURE AND WATER

Water in Crop Production

Plants require water for photosynthesis, growth, and reproduction. Water used by plants is non-recoverable, because some water becomes a part of the plant chemically and remainder is released into the atmosphere. The processes of carbon dioxide fixation and temperature control require plants to transpire enormous amounts of water. Various crops transpire water at rates between 600 to 2000 liters of water per kilogram of dry matter of crops produced (Table 2). The average global transfer of water into the atmosphere from the terrestrial ecosystems by vegetation transpiration is estimated to be about 64% of all precipitation that falls to Earth (Schlesinger, 1997).

The minimum soil moisture essential for crop growth varies. For instance, U.S. potatoes require 25% to 50%, alfalfa 30% to 50%, and corn 50% to 70% (Broner, 2002), while rice in China is reported to require at least 80% soil moisture (Zhi, 2000). Rainfall patterns, temperature, vegetative cover, high levels of soil organic matter, active soil biota, and water runoff all effect the percolation of rainfall into the soil where it will be used by plants.

The water required by food and forage crops ranges from 600 to 3,000 liters of water per kilogram (dry) of crop yield (Table 2). For instance, a hectare of U.S. corn, with a yield of approximately 9,000 kg/ha, transpires about 6 million liters per hectare of water during the growing season (Benham, 1998; Palmer, 2001), while an additional 1 to 2.5 million liters/ha of soil moisture evaporate into the atmosphere (Donahue et al., 1990; Desborough et al., 1996). This means that about 800 mm (8 million liters/ha) of rainfall are required during the growing season for corn production. Even with 800 to 1,000 mm of annual rainfall in the U.S. Corn-Belt region, corn frequently suffers from insufficient water during the critical summer growing period (Troeh and Thompson, 1993).

A hectare of high yielding rice requires approximately 11 million liters/ha of water for an average yield of 7 t/ha (metric tons per hectare) (Snyder, 2000). On average, soybeans require about 5.8 million liters/ha of water for a yield of 3 t/ha (Benham et al., 1999). In contrast, wheat that produces less plant biomass than either corn or rice, requires only about 2.4 million liters/ha of water for a yield of 2.7 t/ha (USDA, 1997) (Table 2). Note, under semi-arid conditions, yields of non-irrigated crops, such as corn, are low (1 to 2.5 t/ha) even when ample amounts of fertilizers are applied (USDA, 1997).

Irrigated Crops and Energy Use

World agriculture consumes approximately 70% of freshwater withdrawn per year (UNESCO, 2000; UNESCO, 2001e). Approximately 17% of the world's cropland is irrigated but produces 40% of the world’s food (FAO, 2002). Worldwide, the amount of irrigated land is slowly expanding, even though salinization, water logging, and siltation continue to decrease its productivity (Gleick, 2002). Despite a small annual increase in total irrigated areas, the per capita irrigated area has been declining since 1990, due to rapid population growth (Postel, 1999; Gleick, 2002). Specifically, global irrigation per capita has declined nearly 10% during the past decade (Postel, 1999; Gleick, 2002), while in the U.S. irrigated land per capita has remained constant at about 0.08 ha (USDA, 2001).

Irrigated U.S. agricultural production accounts for about 40% of freshwater withdrawn (USGS, 2003b), and more than 80% of the water consumed (EPA, 2003). California agriculture accounts for 3% of the state’s economic production, but consumes 85% of the water withdrawn (Myers and Kent, 2001).

Energy Use in Irrigation

Irrigation requires a significant expenditure of fossil energy both for pumping and delivering water to crops. Annually in the U.S., we estimate that 15% of the total energy expended for all crop production is used to pump irrigation water (Hodges et al., 1994). Overall the amount of energy consumed in irrigated crop production is substantially greater than that expended for rainfed crops. For example, irrigated wheat requires the expenditure of more than 3 times more energy than rainfed wheat. Specifically, about 4.2 million kcal/ha/yr are the required energy input for rainfed wheat, while irrigated wheat requires 14.3 million kcal/ha/yr to apply an average of 5.5 million liters of water (NASS/USDA, 1999; Pimentel et al., 2002).

Delivering the 10 million liters of irrigation water needed by a hectare of irrigated corn from surface water sources requires the expenditure of about 880 kWh/ha of fossil fuel (Batty and Keller, 1980). In contrast, when irrigation water must be pumped from a depth of 100 m, the energy cost increases up to 28,500 kWh/ha, or more than 32 times the cost of surface water (Gleick, 1993).

The costs of irrigation for energy and capital are significant. The average cost to develop irrigated land ranges from $3,800/ha to $7,700/ha (Postel, 1999). Thus, farmers must not only evaluate the dollar cost of developing irrigated land, but must also consider the annual costs of irrigation pumping. For example, delivering 7 to 10 million liters/ha of water costs from $750 to $1,000 (Larson et al., 2002; Pitts et al., 2002). About 150,000 ha of agricultural land have already been abandoned in the U.S. due to high pumping costs (Youngquist, 1997).

The large quantities of energy required to pump irrigation water are significant considerations both from the standpoint of energy and water resource management. For example, approximately 8 million kcal of fossil energy are expended for machinery, fuel, fertilizers, pesticides, and partial (15%) irrigation, to produce one hectare of rainfed U.S. corn (Pimentel et al., 2002b). In contrast, if the corn crop were fully irrigated, the total energy inputs would rise to nearly 25 million kcal/ha (2,500 liters of oil equivalents) (Gleick, 1993). In the future, this energy dependency will not only influence the overall economics of irrigated crops but also the selection of specific crops worth irrigating (Pimentel et al., 1997) (Table 2). While a low value crop, like alfalfa, may be uneconomical, other crops might use less water plus have a higher market value (Table 2).

The efficiency varies with irrigation technologies (Postel, 1992, 1993). The most common irrigation methods, flood irrigation and sprinkler irrigation, frequently waste water. In contrast, the use of more focused application methods, such as "drip" or "micro-irrigation" have found favor because of their increased water efficiency. Drip irrigation delivers water to individual plants by plastic tubes and uses from 30% to 50% less water than surface irrigation. In addition to conserving water, drip irrigation reduces the problems of salinization and waterlogging (Tuijl, 1993). Although drip systems achieve up to 95% water efficiency, they are expensive, may be energy intensive, and require clean water to prevent the clogging of the fine delivery tubes (Shock, 2003).

Soil Salinization and Waterlogging in Irrigation

With rainfed crops, salinization is not a problem because the salts are naturally flushed away. But when irrigation water is applied to crops and returns to the atmosphere via plant transpiration and evaporation, dissolved salts concentrate in the soil where they inhibit plant growth. The practice of applying about 10 million liters of irrigation water per hectare each year, results in approximately 5 t/ha of salts being added to the soil (Bouwer, 2002). The salt deposits can be flushed away with added fresh water but at a significant cost (Bouwer, 2002). Worldwide, approximately half of all existing irrigated soils are adversely affected by salinization (Hinrichsen et al., 1998). Each year the amount of world agricultural land destroyed by salinized soil is estimated to be 10 million hectares (Thomas and Middleton, 1993).

In addition, drainage water from irrigated cropland contains large quantities of salt. For instance, as the Colorado River flows through Grand Valley, Colorado, it picks up 580,000 tons of salts per year (USDI, 2001). Based on the drainage area of 20,000 ha, the water returned to the Colorado River contains an estimated 30 t/ha of salts per year (Pugh, 2001). In Arizona, the Salt River and Colorado River deliver a total of 1.6 million tons of salt into south-central Arizona each year (USGS, 1999).

Waterlogging is another problem associated with irrigation. Over time, seepage from irrigation canals and irrigated fields cause water to accumulate in the upper soil levels. Due to water losses during pumping and transport, approximately 60% of the water intended for crop irrigation never reaches the crop (Wallace, 2000). In the absence of adequate drainage, water tables rise in the upper soil levels, including the plant root zone, and crop growth is impaired. Such irrigated fields are sometimes referred to as "wet deserts" because they are rendered unproductive (Postel, 1993). For example in India, waterlogging adversely affects 8.5 million hectares of cropland and results in the loss of as much as 2 million tons of grain every year (ICAR, 1999). To prevent both salinization and waterlogging, sufficient water along with adequate soil drainage must be available to ensure salts and excess water are drained from the soil.

Water Loss in Soil Erosion

Because more than 99% of world food supply comes from the land, an adequate world food supply depends on the continued availability of productive soils (FAO, 1998). Erosion adversely affects crop productivity by reducing the availability of water, diminishing soil nutrients, soil biota, and soil organic matter, and also decreasing soil depth (Pimentel and Kounang, 1998). The reduction in the amount of water available to the growing plants is considered the most harmful effect of erosion, because eroded soil absorbs 87% less water by infiltration than uneroded soils (Guenette, 2001). Soybean and oat plantings intercept approximately 10% of the rainfall, whereas tree canopies intercept 15% to 35% (Plant Canopies, 2003). Thus, deforestation increases water runoff and reduces water availability.

A water runoff rate of about 30% of total rainfall of 800 mm/yr causes significant water shortages for growing crops, like corn, and ultimately lowering crop yields (Troeh and Thompson, 1993). In addition, water runoff, which carries sediments, nutrients, and pesticides from agricultural fields, into surface and ground waters, is the leading cause of non-point source pollution in the U.S. (EPA, 2002). Thus, soil erosion is a self-degrading cycle on agricultural land. As erosion removes topsoil and organic matter, water runoff is intensified and crop yields decrease. The cycle is repeated again with even greater intensity during subsequent rains.

Increasing soil organic matter by applying manure or similar materials can improve the water infiltration rate by as much as 150% (Guenette, 2001). In addition, using vegetative cover, such as intercropping and grass strips, helps slow both water runoff and erosion (Lal, 1993). For example, when silage corn is interplanted with red clover, water runoff can be reduced by as much as 87% and soil loss can be reduced by 78% (Wall et al., 1991). Reducing water runoff in these and other ways is an important step in increasing water availability to crops, conserving water resources, decreasing non-point source pollution, and ultimately decreasing water shortages (NGS, 1995).

Planting trees to serve as shelter belts between fields reduces evapotranspiration from the crop ecosystem by up to 20% during the growing season, thereby reducing non-point source pollution (Mari et al., 1985; Roose, 1996), and increases some crop yields, such as potatoes and peanuts (Snell, 1997). If soil and water conservation measures are not implemented, the loss of water for crops via soil erosion can amount to as much as 5 million liters per hectare per year (Pimentel and Kounang, 1998).

Water Use Livestock Production

The production of animal protein requires significantly more water than the production of plant protein (Pimentel, 2003). Although U.S. livestock directly use only 2% of the total water used in agriculture (Solley et al., 1998), the water inputs for livestock production are substantial because water is required for the forage and grain crops.

Each year the total of 253 million tons of grain are fed to U.S. livestock requiring a total of about 250 x 10^{12} liters of water (USDA-NASS, 2002). Worldwide grain production specifically for livestock requires nearly 3 times the amount of grain that is fed U.S. livestock and 3 times the amount of water used in the U.S. to produce the grain feed (Seglken, 1997; Earth Policy Institute, 2002).

Animal products vary in the amounts of water required for their production (Table 2). For example, producing 1 kg of chicken requires 3,500 liters of water while producing 1 kg of sheep requires approximately 51,000 liters of water in order to produce the required 21 kg of grain and 30 kg of forage to feed these animals (USDA, 2001; Buchanan-Smith, 2002) (Table 2). For open rangeland (instead of confined feedlot production), from 120 kg to 200 kg of forage are required to produce 1 kg of beef. This amount of forage requires 120,000 liters to 200,000 liters of water per kilogram of beef (Thomas, 1987; Dorsett, 2003; Rangeland, 1994). Beef cattle can be produced on rangeland, but a minimum of 200 mm per year of rainfall are needed (Hays and White, 1998).

U.S. agricultural production is projected to expand in order to meet the increased food needs of a U.S. population that is projected to double in the next 70 years (USBC, 2001). The food situation is expected to be more serious in developing countries, such as Egypt and Kenya, because of rapidly growing populations (Rosengrant et al., 2002). Increasing crop yields necessitates a parallel increase in freshwater utilization in agriculture. Therefore, increased crop and livestock production during the next 5 to 7 decades will significantly increase the demand on all water resources, especially in the western, southern, and central United States (USDA, 2001), as well as in many regions of the world with low rainfall.

WATER POLLUTION AND HUMAN DISEASES

Closely associated with the overall availability of water resources is the problem of water pollution and human diseases. At present, approximately 20% of the world’s population lack safe drinking water, and nearly half the world population lack adequate sanitation (GEF, 2002; UN, 2002). This problem is acute in many developing countries that discharge an estimated 95% of their untreated urban sewage directly into surface waters (Chen et al., 2002). For example, of India's 3119 towns and cities, only 8 have full wastewater treatment facilities (WHO, 1992). Downstream, the untreated water is used for drinking, bathing, and washing, resulting in serious human infections and illnesses.

Overall, waterborne infections account for 90% of all human infectious diseases in developing countries (AEI, 2003). Lack of sanitary conditions contributes to approximately 12 million deaths each year, primarily among infants and young children (Hinrichsen et al., 1998). Flooding accounts for about half of the major disasters affecting humans each year (UNESCO, 2001a).

Approximately 40% of U.S. fresh water is deemed unfit for recreational or drinking water uses because of contamination with dangerous microorganisms, pesticides, and fertilizers (UNESCO, 2001b). In the U.S., waterborne infections account for approximately 940,000 infections and approximately 900 deaths each year (Seager, 1995). In recent decades, more U.S. livestock production systems have moved closer to urban areas, causing water and foods to be contaminated with manure (NAS, 2003). In the U.S., the quantity of livestock manure and other wastes produced each year are estimated to be 1.5 billion tons (GAO, 1999). Associated with this kind contamination, the Communicable Disease Center reports that more than 76 million Americans are infected each year with pathogenic E. coli and related foodborne pathogens, resulting in about 5,000 deaths per year (DeWaal et al., 2000).

The incidence of schistosomiasis, which is also associated with contaminated freshwater, is expanding worldwide and each year infects more than 200 million people

(UN, 2003) and currently causes an estimated 20,000 deaths per year (Hinrichsen et al., 1998). Its spread is associated with an increase in habitats, including the construction of dams and irrigation canals suitable for the snail intermediate-host population and accessible for humans to come in contact with the infected water (Shiklomanov, 1993). For example, construction of the Aswan High Dam in Egypt and related irrigation systems in 1968 led to an explosion in Schistosoma mansoni in the human population; increasing from 5% in 1968 to 77% of all Egyptians in 1993 (Shiklomanov, 1993). In 1986, the construction of a dam in Senegal resulted in an increase in schistosomiasis from zero per cent in 1986 to 90% by 1994 (Worldwaterday, 2001).

Mosquito-borne malaria is also associated with water bodies. Worldwide this disease presently infects more than 2.4 billion people (WHO, 1997) and kills about 2.7 million each year (Corey, 2002). Environmental changes, including polluted water, have fostered this high incidence and increase in malaria. For instance, deforestation in parts of Africa exposes land to sunlight and promotes the development of temporary pools of water that favor the breeding of human-biting, malaria-transmitting mosquitoes, Anopheles gambiae (Coluzzi, 1994). In addition, with many African populations doubling every 20 years (PRB, 2003), more people are living in close proximity to mosquito infested aquatic ecosystems. Concurrently, the mosquito vectors are evolving resistance to insecticides that pollute their aquatic ecosystems, while protozoan pathogens are evolving resistance to the over-used antimalarial drugs. Together these factors are reducing the effectiveness of many malaria control efforts (Olliaro et al., 1996).

Another serious water-borne infectious disease that can be transmitted via air, water, and food, is tuberculosis (TB). At present, approximately 2 billion people are infected with TB with the number increasing each year (WHO, 2001).

Presently, worldwide about 2 billion people are infected with one or more helminth species, either by direct penetration or by use of contaminated water or food (Hotez et al., 1996). In locations where sanitation is poor and overcrowding is rampant, as in parts of urban Africa, up to 90% of the population may be infected with one or more helminthes (Stephenson, 1994).

In addition to helminthes and microbe pathogens, there are many chemicals that contaminate water and have negative impacts on human health as well as natural biota. For example, an estimated 3 billion kg of pesticides are applied worldwide each year in agriculture (Pimentel, 1997). USEPA also allowed the application of sludge to agricultural land and this sludge is contaminated with heavy metals and other toxics (McBride, 1995). Many of these agricultural chemicals, including nitrogen fertilizer, contaminate aquatic ecosystems by leaching and runoff and result in eutrophication of aquatic ecosystems and other environmental problems (Howarth, 2003). Worldwide, pesticides alone contribute to an estimated 26 million human poisonings and 220,000 deaths each year (Richter, 2002).

LIMITS TO WATER USE

Costs of Water Treatment

Increases in pollution of surface and groundwater resources not only pose a threat to public and environmental health, but also contribute to the high costs of water treatment, thus further limiting the availability of water for use. Depending on water quality and the purification treatments used, potable water costs an average of 50¢/1,000 liters in the U.S.

and range up to $1.91/1000 liters in Germany (UNESCO, 2001c). Appropriate water pricing is important for improved water demand and conservation of water (UNESCO, 2001c; Minter et al., 2002).

The cost of treating U.S. sewage for release into streams and lakes ranges from 55¢/1000 liters for small plants to 30¢/1000 liters for large plants (Gleick, 2000). Sewage effluent, when properly treated to make it safe for use as potable water, is relatively expensive and ranges in costs from $1.00 to $2.65 /1000 liters (Gleick, 2000).

Purifying and reducing the number of polluting microbes in water, as measured by the BOD (biological oxygen demand), is energy costly. Removing 1 kg of BOD requires 1 kWh (Trobish, 1992). In this process, most of the cost for pumping and delivering water is for energy and equipment. Delivering 1 m^3 (1,000 liters) of water in the U.S. requires the expenditure of about 1.3 kWh. Excluding only the energy for pumping sewage, the cost and amount of energy required to process 1000 liters of sewage in a technologically advanced wastewater treatment plant is about 65¢ and requires about 0.44 kWh of energy (Downing et al., 2002). Looking to the future, the costs of water treatment and the energy required to purify water will increase.

Dependence on the oceans for freshwater has major problems. When brackish water is desalinized, the energy costs are high, ranging from 25¢ to 60¢/1000 liters, while seawater desalinization ranges from 75¢ to $3/1000 liters (Buros, 2000). In addition, transporting large volumes of desalinized water adds to the costs.

Loss of Biodiversity

Natural diversity of species is essential to maintaining a quality environment, as well as productive agriculture and forestry. The water required to keep natural ecosystems, especially the plants, functioning has been appropriately termed *green water* (Falkenmark, 1995).

The biodiversity of all species throughout the world is adversely affected when water resources are reduced and/or polluted. Thus the drastic drainage of more than half of U.S. wetlands (National Wildlife Federation, 2002) that contain 45% of our federally endangered and threatened species, has seriously disrupted these ecosystems (Havera et al., 1997). In 2002, approximately 33,000 salmon perished in the Klamath River when farmers were allowed to withdraw increased volumes of water for irrigation (Service, 2003). Pear farmers in the Rogue Valley of Oregon use significant amounts of the water before it reaches the Klamath Lake, leaving only 616 million m^3 of water per year for wildlife and other farmers downstream (Fattig, 2001). Similarly, over pumping and upstream removal of water have reduced biodiversity in the Colorado River and the Rio Grande River (Greenwald, 1999). The major alteration of the natural water flow in the lower portion of the U.S. Colorado River has been responsible for 45 species of plants and animals to be listed as federally endangered or threatened (Glenn et al., 2001).

Effect of Climate and Environmental Change on Water Availability

Estimates of water resources and their future availability can only be based on present world climate patterns. The continued loss of forests and other vegetation plus the accumulation of carbon dioxide, methane gas, and nitrous oxides in the atmosphere are projected to lead to global climate change. Over time, such changes may alter present precipitation and temperature patterns throughout the world (Downing and Parry, 1994; IPCC, 2002). With major shifts in water availability, future agricultural, forestry, biodiversity, and diverse human activities will be impacted.

For example, if as projected, California experiences a 50% decrease in mountain snowpack due to global warming (Knowles and Cayon, 2002), this would change both the timing and intensity of seasonal surface water flow (Miller et al., 2001). In contrast, Canada might benefit from warming with extended growing seasons, but even this region eventually could face water shortages (Parry and Carter, 1989; IPCC, 2002). If, as projected, the annual temperatures in the U.S. Corn-Belt rise 3 to 4 degrees C, rainfall might decline by about 10% (Myers and Kent, 2001), evaporation rates from the soil may increase and limit corn production in the future (Rosenzweig and Parry, 1994).

The predicted global warming, along with increased human food requirements can be expected to alter and probably increase world irrigation needs by 30% to ensure food security (Doll, 2002). Other serious impacts of global warming could increase deforestation, desertification, soil erosion, and loss of biodiversity. All of these major changes suggest the reduction of water availability for humans, for all other living organisms and also for crop and forest production (Heywood, 1995; Root et al., 2003).

ECONOMIC COSTS OF WATER SUBSIDIES

The relatively high cost of treating and delivering water has led many world governments to subsidize water for agriculture and household use. For example, some U.S. farmers pay as little as 1¢ to 5¢/1000 liters they use in irrigation, while the public pays from 30¢ to 80¢ per 1000 liters of treated water for personal use (Gleick, 2000). Farmers in the Imperial Irrigation District of California pay $15.50 in delivery fees for 1.2 million liters of water (Murphy, 2003). Some investigators suggest that if U.S. farmers paid the full cost of water, they would have to conserve and manage irrigation water more effectively (Willardson, et al., 1994).

The construction cost subsidy for federally-subsidized western U.S. irrigated cropland amounts to about $5,000 per hectare (Postel, 1999), and represents an annual construction cost subsidy of about $440 per ha/yr over the life of the project (USC, 1989; Pimentel et al., 1997). The total annual government subsidy is estimated to range from $2.5 billion to $4.4 billion for the 4.5 million hectares of irrigated land in the western United States (Myers and Kent, 2001; VanBeers and deMoor, 2001). Worldwide, from f94 to 1998 governmental water subsidies totaled $45 billion per year for non-Organization for Economic Cooperation and Development (OECD) countries and $15 billion for OECD counties (VanBeers and deMoor, 2001). During the same period, agricultural subsidies per year total $65 billion for non-OECD and $355 billion for OECD countries (VanBeers and deMoor, 2001).

According to the World Bank (2003), the objectives of fair water pricing are: (1) to seek revenue to pay for the operations and maintenance of water availability; (2) improve water-use efficiency; and (3) recover the full costs of water pumping and treatment. However, in general there appear to be problems with some private, for profit companies operating water systems for communities and regions. Often the companies operate as monopolies which can lead to unfair pricing practices (Schalch, 2003).

If U.S. prices of gasoline and diesel energy increase to approximately $10 per gallon, it follows that irrigation costs will continue to escalate (Pimentel and Pimentel, 1996) from the current $2.9 billion per year (USBC, 1995). Since vegetable and fruit crops return more per dollar invested in irrigation water than field crops, farmers may have to reassess the crops they grow. For example, in Israel 1000 liters of water from irrigation produces 79¢ worth of groundnuts and 57¢ worth of tomatoes, but only 13¢ worth of corn grain and 12¢ worth of wheat (Fishelon, 1994).

CONFLICTS OVER WATER USE

The rapid rise in withdrawal of freshwater for agricultural irrigation and for other uses that have accompanied population growth has spurred serious conflicts over water resources both within and between countries (FAO, 2000). In part the conflicts over fresh water is due to the sharing of fresh water by countries and regions. Currently there are 263 transboundary river basins sharing water resources (UNESCO, 2001d). Worldwide such conflicts have increased from an average of 5 per year in the 1980s to 22 in 2000 (GEF, 2002). In 23 countries where data are available, conflicts related to agricultural use of water cost an estimated $55 billion between 1990 and 1997 (GEF, 2002).

At least 20 nations obtain more than half their water from rivers that cross national boundaries (Gleick, 1993), and 14 countries receive 70% or more of their surface water resources from rivers that are outside their borders (Alavian, 2003; Cech, 2003). For example, Egypt obtains 97% of its freshwater from the Nile River (Alavian, 2003), the second longest in the world, which is also shared by the Sudan, Ethiopia, Egypt, Burundi, Kenya, Rwanda, Tanzania, Zaire, Eritrea, and Uganda (Postel, 1995; Alavian, 2003). Indeed, the Nile River is so overused that during parts of the year little or no freshwater reaches the Mediterranean Sea (Postel, 1995).

Historically, the Middle East region has had the most conflicts over water, largely because it has less available water per capita than most other regions, and every major river crosses international borders (Fisher and Hossein, 2001; Gleick et al., 2002). Furthermore, the human populations in these countries are increasing rapidly, some having doubled in the last 20 to 25 years, placing additional stress on the difficult political climate (PRB, 2003).

The distribution of river water also creates conflicts between several U.S. states as well as problems between the U.S. and Mexico. California, Nevada, Colorado, New Mexico, Utah, Arizona, and Mexico all depend on Colorado River water. In a normal year, little water reaches Mexico, and little or no water reaches the Gulf of California (Postel et al., 1996; Gleick, 2000).

CONSERVING WATER RESOURCES

Conserving world water must be a priority of individuals, communities, and countries. An important approach is to find ways to facilitate the percolation of rainfall into the soil instead of allowing it to runoff into streams and rivers. For example, the increased use of trees and shrubs make it possible to catch and slow water runoff by 10% to 20%, thereby conserving water before it reaches streams, rivers, and lakes (Urban Forestry, 2002). This approach also reduces flooding.

Maintaining crop, livestock, and forest production requires conserving all water resources available, including rainfall (Cech, 2003). Some practical strategies that support water conservation for crop production include: (1) monitoring soil water content; (2) adjusting water application needs to specific crops; (3) applying organic mulches to prevent water loss and improve water peculation, through reduced water runoff and evaporation; (4) using crop rotations that reduce water runoff; (5) preventing the removal of biomass from land; (6) increasing use of trees and shrubs to slow water runoff; and (7) employing precision irrigation in water delivery systems, such as drip irrigation, that will result in efficient crop watering (Miller, 1999; IRZ, 2002).

In forest areas, it will be necessary to avoid clear cutting and humans should employ sound forest management. Trees also benefit urban areas that have high rates of runoff. Since water runoff is rapid from roofs, driveways, roads, and parking lots, the water can be collected in cisterns and constructed ponds. Estimated runoff rates from urban area were 72% higher than areas with forest cover (Boulder, 2003).

Given that many aquifers are being over drafted, government efforts are needed to limit the pumping to sustainable withdrawal levels or at the known recharge rate. Integrated water resource management programs offer many opportunities to conserve water resources for everyone, farmers and the public (Serageldin, 2003).

USING WATER WISELY IN THE FUTURE

Providing adequate quantities of pure freshwater for humans and their diverse activities appears to be a major problem worldwide. If further competition for water resources within regions and between countries continues to escalate, and remain unresolved this, too, will have negative impacts on essential freshwater supplies for personal and agricultural use. Even now, freshwater resources for food production and other human needs are declining because of increasing demand (UNEP, 2003b; Gleick 2004) and becoming outright scarce in arid regions. Particularly in arid regions, where groundwater resources are the primary sources of water, future irrigation, industrial, and urban water use must be carefully managed to prevent exhausting the aquifers.

More effective use of water in all agricultural production, that consumes 70% of world freshwater, can be achieved by providing farmers with incentives to conserve water and soil resources. Employing methods of controlling erosion will help conserve water in crop production. Protecting forests, wetlands, natural ecosystems and other biological resources all enhance water conservation.

Globally, agriculture and industries that continue to pollute water used by humans and other organisms adversely affect public health and biodiversity. Many developing countries need immediate assistance in improving their drinking water sources and sanitary facilities.

Future water resource availability will depend on the efforts of individuals, communities, and regions to conserve and protect the quality of water (GWP 2004; IWRM 2004). The success of these efforts will determine our ability to produce adequate food resources and protect public health in the future.

Table 1. Regions of the world with water problems (based on the criterion that yearly water availability per capita is less than 1,000,000 liters/yr) and their per capita water availability (Falkenmark and Lindh, 1993).

Region	Water availability per capita 1000 liters/yr
Egypt	40
West Bank	126
Jordan	255
Saudi Arabia	300
Israel	376
Syria	440
Kenya	610
United States (comparison)	1,862

Table 2. Estimated liters of water required to produce 1 kilogram of food and forage crops.

Crop	Liters/kg	Source
Soybeans	2000	USDA-NASS, 1998
Rice	1600	Synder, 2000
Sorghum	1300	Klocke et al., 1996
Alfalfa	1100	USDA-NASS, 1998
Wheat	900	USDA, 1997
Corn	650	Benham et al., 1999; Palmer, 2001
Potatoes (dry)	630	USDA-NASS, 1998
Millet	272	Baltensperger et al., 1996
Broiler chicken	3500	Pimentel, 2003c
Pig	6000	Pimentel, 2003c
Beef	43,000	Pimentel, 2003c
Sheep	51,000	Pimentel, 2003c

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