

Water Resources: Agricultural and Environmental Issues

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The increasing demands placed on the global water supply threaten biodiversity and the supply of water for food production and other vital human needs. Water shortages already exist in many regions, with more than one billion people without adequate drinking water. In addition, 90% of the infectious diseases in developing countries are transmitted from polluted water. Agriculture consumes about 70% of fresh water worldwide; for example, approximately 1000 liters (L) of water are required to produce 1 kilogram (kg) of cereal grain, and 43,000 L to produce 1 kg of beef. New water supplies are likely to result from conservation, recycling, and improved water-use efficiency rather than from large development projects.

Keywords: water resources, environmental policy, agriculture

Water is essential for maintaining an adequate food supply and a productive environment for the human population and for other animals, plants, and microbes worldwide. As human populations and economies grow, global freshwater demand has been increasing rapidly (Hinrichsen et al. 1998, Postel 1999, Rosegrant et al. 2002, Shiklomanov and Rodda 2003, UNEP 2003a, Gleick 2004). In addition to threatening the human food supply, 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. 2004).

Humans obtain the great majority of their nutrients from crops and livestock, and these nutrient sources require water, land, and energy for production (Pimentel et al. 2004). Food supplies (cereal grains) per capita have declined by 17% over the past 20 years, in part because of an increase in human population and concurrent shortages of fresh water and cropland (FAO 1961–2002). Shortages in food supplies have in part contributed to the global problem of more than 3 billion malnourished people in the world (WHO 2004a). Two of the most serious malnutrition problems are iron deficiency, affecting 2 billion people, and protein or calorie deficiency, affecting nearly 800 million people (WHO 2002, 2004b). Iron deficiency and protein or calorie deficiency each result in about 8 million deaths each year (WHO 2002).

The world population currently numbers 6.3 billion, with more than a quarter million people added each day (PRB 2003). The United Nations (UN 2001) estimates that the global population will increase to approximately 9.4 billion people by 2050. Population growth, accompanied by increased water use, will not only severely reduce water avail-

ability per person but also create stress on biodiversity in the entire global ecosystem (Pimentel et al. 2004). Other major factors that limit water availability include rainfall, temperature, evaporation rates, soil quality, vegetation type, and 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. In this article, we analyze water use by individuals and especially by agricultural systems, reporting the interrelationships that exist among population growth, water use and distribution, the status of biodiversity, the natural environment, and the impacts of waterborne human diseases.

Hydrologic cycle

Of the estimated 1.4×10^{18} cubic meters (m^3) of water on Earth, more than 97% is in the oceans (Shiklomanov and Rodda 2003). Approximately 35×10^{15} m^3 of Earth's water is fresh water, of which about 0.3% is held in rivers, lakes, and reservoirs (Shiklomanov and Rodda 2003). The remainder of the fresh water is stored in glaciers, permanent snow, and groundwater aquifers. Earth's atmosphere contains about 13×10^{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 (159,300 exajoules) of solar energy cause

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evaporation that moves about $577 \times 10^{12} \text{ m}^3$ of water from Earth's surface into the atmosphere. Of this evaporation, 86% is from the oceans (Shiklomanov 1993). Although only 14% of the water evaporation is from land, about 20% ($115 \times 10^{12} \text{ m}^3$ per year) of the world's precipitation falls on land, with the surplus water returning to the oceans through 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 (Pimentel et al. 2004).

Availability of water

Although water is considered a renewable resource because it is replenished by rainfall, its availability is finite in terms of the amount available per unit of time in any one region. The average precipitation for most continents is about 700 millimeters (mm) per year (7 million liters [L] per hectare [ha] per year), but this amount varies among and within continents (Shiklomanov and Rodda 2003). In general, water in a nation is considered scarce when its availability drops below 1 million L per capita per year (table 1; Engleman and LeRoy 1993). Thus, Africa is relatively arid, despite its average rainfall of 640 mm per year, because its high temperatures and winds foster rapid evaporation (Pimentel et al. 2004). Regions that receive low rainfall (less than 500 mm per year) experience serious water shortages and inadequate crop yields. For example, 9 of the 14 Middle Eastern countries (including Egypt, Jordan, Saudi Arabia, Israel, Syria, Iraq, and Iran) have insufficient fresh water (Myers and Kent 2001, UNEP 2003a).

When managing water resources, the total agricultural, societal, and environmental system must be considered. In the United States, substantial withdrawals from the lakes, rivers, groundwater, and reservoirs that are used to meet the needs of individuals, cities, farms, and industries already stress the availability of water in some parts of the country (Alley et al. 1999). 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 flow into Texas (Pimentel et al. 2004).

Groundwater resources

Approximately 30% ($11 \times 10^{15} \text{ m}^3$) of all fresh water 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 earth's surface. Aquifers are replenished slowly by rainfall, with an average recharge rate that ranges from 0.1% to 3% per year (Pimentel et al. 2004). Assuming an average recharge rate of 1%, this leaves only $11 \times 10^{13} \text{ m}^3$ of water per year available for sustainable use worldwide. At present, world groundwater aquifers provide approximately 23% of the water used throughout the world (USGS 2003a). Irrigation for US agriculture relies heavily on groundwater, with 65% of irrigation water being pumped from aquifers (Pimentel et al. 2004).

Population growth, increased agricultural irrigation, 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. From 1950 to 1990, this uncontrolled withdrawal caused water tables to fall by more than 30 m in some US regions (Brown 2002). The overdraft of global groundwater is estimated to be about $2 \times 10^{11} \text{ m}^3$, or much higher than the average recharge rate (Pimentel et al. 2004). For example, the capacity of the Ogallala aquifer, which underlies parts of Nebraska, South Dakota, Colorado, Kansas, Oklahoma, New Mexico, and Texas, has decreased 33% since about 1950. Withdrawal from the Ogallala is three times faster than its recharge rate (Gleick et al. 2002). Water from aquifers is being withdrawn more than 10 times faster than the recharge rate 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 per year since the late 1990s (Brown 2002). Withdrawals 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 some aquifers are mined, the surface soil area tends to sink, making it impossible for the aquifer to be refilled (Pimentel et al. 2004).

Stored water resources

In the United States, many dams were built in arid regions during the early 20th century in an effort to increase the quantity of available water. The construction of large dams and associated conveyance systems to meet water demand has slowed down in the United States (Pimentel et al. 2004). However, the expected life of a dam is 50 years, and 85% of US dams will be more than 50 years old by 2020 (Pimentel et al. 2004). Dam construction continues in many develop-

Table 1. Annual water availability per capita for seven regions with water problems (annual water availability per capita of less than 1 million liters per year) and for the United States.

Region	Water availability per capita (thousands of liters per year)
Egypt	40
West Bank	126
Jordan	255
Saudi Arabia	300
Israel	376
Syria	440
Kenya	610
United States	1862

Source: Falkenmark and Lindh (1993).

ing countries worldwide. Over time, the capacity of all dams is reduced as silt accumulates behind them. An estimated 1% of the storage capacity of the world's dams is lost each year because of silt accumulation (Pimentel et al. 2004).

Water use and consumption

Water from different resources is withdrawn both for use and for 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 wastewater). In contrast, *consumption* means that the withdrawn water is nonrecoverable. For example, evapotranspiration of water from plants is released into the atmosphere and is considered nonrecoverable.

The water content of living organisms ranges from 60% to 95%; humans are about 60% water (Pimentel et al. 2004). To sustain health, humans should drink from 1.5 to 2.5 L water per person per day. In addition to drinking water, Americans use about 400 L per person per day for cooking, washing, disposing of waste, and other personal uses (USBC 2003). In contrast, 83 other countries report an average for personal use of water per person per day below 100 L (Gleick et al. 2002).

Current US freshwater withdrawals, including those for irrigation, total about 1600 billion L per day, or about 5500 L per person per day. Of this amount, about 80% comes from surface water, and 20% is withdrawn from groundwater resources (USBC 2003). Worldwide, the average withdrawal is 1970 L per person per day for all purposes (Gleick et al. 2002). Approximately 70% of the water withdrawn worldwide is consumed and nonrecoverable.

Agriculture and water

Plants require water for photosynthesis, growth, and reproduction. The water used by plants is nonrecoverable, because some water becomes a part of the chemical makeup of the plant and the 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 use water at rates between 300 and 2000 L per kilogram (kg) dry matter of crops produced (table 2). The average global transfer of water into the atmosphere by vegetation transpiration from terrestrial ecosystems is estimated to be about 64% of all precipitation that falls to Earth (Pimentel et al. 2004).

The minimum soil moisture essential for crop growth varies. For instance, US potatoes require soil moisture levels of 25% to 50%; alfalfa, 30% to 50%; and corn, 50% to 70% (Pimentel et al. 2004). Rice in China is reported to require at least 80% soil moisture (Pimentel et al. 2004). Rainfall patterns, temperature, vegetative cover, high levels of soil organic matter, active soil biota, and water runoff all affect the percolation of rainfall into the soil, where it is used by plants.

The water required by food and forage crops ranges from about 300 to 2000 L per kg dry crop yield (table 2). For instance, in the United States, 1 ha of corn, with a yield of approximately 9000 kg per ha, transpires about 6 million L

water per ha during the growing season (Pimentel et al. 2004), while an additional 1 million to 2.5 million L per ha of soil moisture evaporate into the atmosphere (Pimentel et al. 2004). This means that the growing season for corn production requires about 800 mm rainfall (8 million L per ha). Even with annual rainfall of 800 to 1000 mm in the US Corn Belt, corn frequently suffers from insufficient water during the critical summer growing period (Pimentel et al. 2004).

A hectare of high-yielding rice requires approximately 11 million L water per ha for an average yield of 7 metric tons (t) per ha (Pimentel et al. 2004). On average, soybeans require about 6 million L water per ha for a yield of 3.0 t per ha (Pimentel et al. 2004). In contrast, wheat, which produces less plant biomass than either corn or rice, requires only about 2.4 million L per ha of water for a yield of 2.7 t per ha (table 2). Under semiarid conditions, yields of nonirrigated crops, such as corn, are low (1.0 to 2.5 t per ha) even when ample amounts of fertilizers are applied (Pimentel et al. 2004).

Irrigated crops and land use. World agriculture consumes approximately 70% of the fresh water withdrawn per year (UNESCO 2001a). Only about 17% of the world's cropland is irrigated, but this irrigated land produces 40% of the world's food (FAO 2002). Worldwide, the amount of irrigated land is slowly expanding, even though salinization, waterlogging, and siltation continue to decrease its productivity (Gleick 2002). Despite a small annual increase in total irrigated area, the irrigated area per capita has been declining since 1990 because of 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 irrigated land per capita in the United States has remained constant at about 0.08 ha (USDA 2003). Irrigated agricultural production accounts for about 40% of the fresh water withdrawn in the United States (USGS 2003b) and more than 80% of the water consumed (Pimentel et al. 2004). California's agriculture accounts for only 3% of the state's

Table 2. Estimated amount of water required to produce crops and livestock.

Crop or livestock	Water required (liters per kilogram)
Crop	
Soybeans	2000
Rice	1600
Sorghum	1300
Alfalfa	1100
Wheat	900
Corn	650
Potatoes (dry)	630
Millet	272
Livestock	
Broiler chicken	3500
Pig	6000
Beef cattle	43,000
Sheep	51,000

Source: Pimentel and colleagues (2004).

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 for delivering water to crops. In the United States, we estimate that 15% of the total energy expended annually for all crop production is used to pump irrigation water (Pimentel et al. 2004). 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 three times the energy needed to produce rainfed wheat. Rainfed wheat requires an energy input of only about 4.2 million kilocalories (kcal) per ha per year, while irrigated wheat requires 14.3 million kcal per ha per year to supply an average of 5.5 million L water (Pimentel et al. 2004). Delivering 10 million L water from surface water sources to irrigate 1 ha of corn requires the expenditure of about 880 kilowatt-hours (kWh) of fossil fuel per ha. In contrast, when irrigation water must be pumped from a depth of 100 m, the energy cost increases to 28,500 kWh per 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 \$3800 to \$7700 per ha (Postel 1999). Thus, farmers must not only evaluate the costs of developing irrigated land but also consider the annual costs of irrigation pumping. For example, delivering 7 million to 10 million L water per ha costs \$750 to \$1000 (Pimentel et al. 2004). About 150,000 ha of agricultural land in the United States have already been abandoned because of high pumping costs (Pimentel et al. 2004).

The large quantities of energy required to pump irrigation water are significant considerations both from the standpoint of energy and of water resource management. For example, in the United States, approximately 8 million kcal of fossil energy are expended for machinery, fuel, fertilizers, pesticides, and partial (15%) irrigation to produce 1 ha of rainfed corn (Pimentel et al. 2004). In contrast, if the corn crop were fully irrigated, the total energy input would rise to nearly 25 million kcal per ha (2500 L of oil equivalent) (Pimentel et al. 2004). In the future, this energy dependency will influence not only the overall economics of irrigated crops but also the selection of specific crops worth irrigating (table 2; Pimentel et al. 2004). While a low-value crop such as alfalfa may be uneconomical, other crops may use less water and have a higher market value (table 2).

The efficiency of irrigating crops varies with irrigation technologies (Pimentel et al. 2004). The most common irrigation methods, flood irrigation and sprinkler irrigation, frequently waste water. In contrast, more focused application methods, such as drip irrigation and microirrigation, have found favor because of their greater water efficiency. Drip irrigation, which delivers water to individual plants through plastic tubes, uses 30% to 50% less water than surface irrigation. In addition to conserving water, drip irrigation reduces

the problems of salinization and waterlogging (van 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 (Pimentel et al. 2004).

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 through plant transpiration and evaporation, dissolved salts concentrate in the soil, where they inhibit plant growth. The practice of applying about 10 million L irrigation water per ha each year results in approximately 5 t salts per ha 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). The amount of world agricultural land destroyed by salinized soil each year is estimated to be 10 million ha (Pimentel et al. 2004). 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 t 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 salts per ha per year (Pugh 2001). In Arizona, the Salt River and Colorado River deliver a total of 1.6 million t salts into south-central Arizona each year (Pimentel et al. 2004).

Waterlogging is another problem associated with irrigation. Over time, seepage from irrigation canals and irrigated fields causes water to accumulate in the upper soil levels. Because of 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 (Pimentel et al. 2004). For example, in India, waterlogging adversely affects 8.5 million ha of cropland and results in the loss of as much as 2 million t grain every year (Pimentel et al. 2004). To prevent both salinization and waterlogging, sufficient water and adequate soil drainage must be available to ensure that salts and excess water are drained from the soil.

Water runoff and soil erosion. Because more than 99% of the world's food comes from the land, an adequate global food supply depends on the continued availability of productive soils (FAO 1998). Erosion adversely affects crop productivity by reducing the availability of water; by diminishing soil nutrients, soil biota, and soil organic matter; and by decreasing soil depth (Pimentel et al. 2004). The reduction in the amount of water available to growing plants is considered the most harmful effect of erosion, because eroded soil absorbs 87% less water through infiltration than uneroded soil (Pimentel

et al. 2004). Soybeans and oats intercept approximately 10% of the rainfall in areas where they are planted, whereas tree canopies intercept 15% to 35% (Pimentel et al. 2004). Thus, the removal of trees increases water runoff and reduces water availability.

Given a total rainfall of 800 mm per year, a water runoff rate of about 30% causes significant water shortages for growing crops such as corn, ultimately lowering crop yields (Pimentel et al. 2004). In addition, water runoff, which carries sediments, nutrients, and pesticides from agricultural fields into surface water and groundwater, is the leading cause of nonpoint-source pollution in the United States (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 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% (Pimentel et al. 2004). In addition, the use of vegetative cover, such as grass strips, and intercropping help 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% (Pimentel et al. 2004). Reducing water runoff in these and other ways is an important step in increasing water availability to crops, conserving water resources, decreasing nonpoint-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 nonpoint-source pollution (Pimentel et al. 2004). Tree plantings also increase the yields of some crops, such as potatoes and peanuts (Snell 1997). If soil and water conservation measures are not implemented, the loss of water for crops through soil erosion may amount to as much as 5 million L per ha per year (Pimentel et al. 2004).

Water use in livestock production. The production of animal protein requires significantly more water than the production of plant protein (Pimentel et al. 2004). Although US livestock directly uses only 2% of the total water used in agriculture (Solley et al. 1998), the indirect water inputs for livestock production are substantial because of the water required for forage and grain crops. Each year, a total of 253 million t grain are fed to US livestock, requiring a total of about 25×10^{13} L water (Pimentel et al. 2004). Worldwide grain production specifically for livestock requires nearly three times the amount of grain that is fed to US livestock and three times the amount of water used in the United States to produce grain feed (Pimentel et al. 2004).

Animal products vary in the amounts of water required for their production (table 2). For example, producing 1 kg chicken requires 3500 L water, whereas producing 1 kg sheep (fed on 21 kg grain and 30 kg forage) requires approximately

51,000 L water (table 2; USDA 2003, Pimentel et al. 2004). If cattle are raised on open rangeland and not in confined feedlot production, 120 to 200 kg forage are required to produce 1 kg beef. This amount of forage requires 120,000 to 200,000 L water per kg (Pimentel et al. 2004), or a minimum of 200 mm rainfall per year (Pimentel et al. 2004).

Agricultural production in the United States is projected to expand to meet the increased food needs of the US population, which is expected to double in the next 70 years (USBC 2003). Developing countries are expected to feel the impacts of this food crisis to a greater extent as demands approach those of developed countries and populations continue to rise (Rosegrant et al. 2002). Increasing crop yields necessitate a parallel increase in the use of fresh water 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 2003) and 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 lacks safe drinking water, and nearly half the world population lacks adequate sanitation (GEF 2002, UNESCO 2002). This problem is acute in many developing countries, which discharge an estimated 95% of their untreated urban sewage directly into surface waters (Pimentel et al. 2004). 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 (Pimentel et al. 2004). The lack of sanitary conditions contributes to approximately 12 million deaths each year, primarily among infants and young children (Hinrichsen et al. 1998).

Approximately 40% of US fresh water is deemed unfit for drinking or recreational use because of contamination by dangerous microorganisms, pesticides, and fertilizers (UNESCO 2001b). In the United States, waterborne infections account for approximately 940,000 infections and approximately 900 deaths each year (Pimentel et al. 2004). In recent decades, more US livestock production systems have moved closer to urban areas, causing water and food to be contaminated with manure (BANR 2003). The quantity of livestock manure and other wastes produced each year in the United States is estimated to be 1.5 billion t (Pimentel et al. 2004). According to the Centers for Disease Control, each year more than 76 million Americans are infected and 5000 die as a result of pathogenic *Escherichia coli* and related foodborne pathogens, which are associated with this kind of contamination (DeWaal et al. 2000).

The incidence of schistosomiasis, which is also associated with contaminated fresh water, is expanding worldwide. Each

year this disease, caused by a parasitic worm, is contracted by more than 200 million people and causes an estimated 20,000 deaths (Hinrichsen et al. 1998). Its spread is associated with an increase in schistosome habitat, including the construction of dams and irrigation canals that are suitable for the parasite's intermediate host (a snail) and accessible to humans, allowing them 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 of *Schistosoma mansoni* in the human population, with the number of infected people increasing from 5% of the Egyptian population in 1968 to 77% in 1993 (Shiklomanov 1993). In 1986, the construction of a dam in Senegal resulted in an increase in schistosomiasis from 0% in 1986 to 90% in 1994 (Pimentel et al. 2004).

Mosquito-borne malaria is also associated with water bodies. Worldwide, this disease infects more than 2.4 billion people and kills about 2.7 million each year (Pimentel et al. 2004). Environmental changes, including polluted water, have fostered this high incidence of 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 the human-biting, malaria-transmitting mosquito *Anopheles gambiae* (Pimentel et al. 2004). 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 the insecticides that pollute their aquatic ecosystems, while protozoan pathogens are evolving resistance to the overused antimalarial drugs. Together, these factors are reducing the effectiveness of many malaria control efforts (Pimentel et al. 2004).

Another serious infectious disease associated with poor water quality is tuberculosis, which can be transmitted through air, water, or food. At present, approximately two billion people are infected with tuberculosis, with the number increasing each year (Pimentel et al. 2004). In addition, about two billion people worldwide are infected with one or more types of helminth (e.g., tapeworm, liver fluke, leech), either through direct penetration of their skin or through the use of contaminated water or food (Hotez et al. 1996). In locations where sanitation is poor and overcrowding is rampant, such as parts of urban Africa, up to 90% of the population may be infected with one or more helminth species (Pimentel et al. 2004).

In addition to helminths and microbe pathogens, many chemicals contaminate water and have negative impacts on human health and natural biota. For example, an estimated 3 billion kg pesticides are applied worldwide in agriculture each year (Pimentel et al. 2004). The US Environmental Protection Agency also allows the application of sludge to agricultural land, and this sludge is contaminated with heavy metals and other toxins (Pimentel et al. 2004). Many of these agricultural chemicals, including nitrogen fertilizer, contaminate aquatic ecosystems through leaching and runoff, resulting in the eutrophication of aquatic ecosystems and other environmental problems (Howarth 2003). Worldwide, pesticides alone con-

tribute to an estimated 26 million human poisonings and 220,000 deaths each year (Richter 2002).

Limits to water use

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 on the purification treatments used, potable water costs an average of \$0.50 per 1000 L in the United States and up to \$1.91 per 1000 L in Germany (UNESCO 2001c). The cost of treating US sewage for release into streams and lakes ranges from \$0.30 per 1000 L for large treatment plants to \$0.55 per 1000 L for smaller plants (Gleick 2000). Sewage effluent is relatively expensive when properly treated to make it safe for use as potable water, ranging in cost from \$1.00 to \$2.65 per 1000 L (Gleick 2000).

Purifying and reducing the number of polluting microbes in water, as measured by biological oxygen demand (BOD), is costly in terms of energy. Removing 1 kg BOD requires 1 kWh (Pimentel et al. 2004). In this process, most of the cost for pumping and delivering water is for energy and equipment. Delivering 1 m³ (1000 L) water in the United States requires the expenditure of about 1.3 kWh. Processing 1000 L sewage in a technologically advanced wastewater treatment plant costs about \$0.65 and requires about 0.44 kWh, excluding the energy for pumping sewage (Pimentel et al. 2004). In the future, the costs of water treatment and the energy required to purify water are likely to increase.

Dependence on the oceans for fresh water involves major problems. When brackish water is desalinated, the energy costs are high, ranging from \$0.25 to \$0.60 per 1000 L. Seawater desalination is even more expensive, ranging from \$0.75 to \$3.00 per 1000 L (Buros 2000). Transporting large volumes of desalinated water adds to the cost of water from marine or brackish sources.

Economic costs of water subsidies. Appropriate water pricing is important for improved water demand and conservation of water (UNESCO 2001d, Pimentel et al. 2004). The relatively high cost of treating and delivering water has led many world governments to subsidize water for agricultural and household use. For example, some US farmers pay as little as \$0.01 to \$0.05 per 1000 L used in irrigation, while the public pays \$0.30 to \$0.80 per 1000 L treated water for personal use (Gleick 2000). Farmers in the Imperial Irrigation District of California pay only \$15.50 in delivery fees for 1.2 million L water (Murphy 2003). Some investigators suggest that if US farmers paid the full cost of water, they would have to conserve and manage irrigation water more effectively (Pimentel et al. 2004).

The federal construction cost subsidy for irrigated cropland in the western United States amounts to about \$5000 per ha, representing an annual subsidy of about \$440 per ha per year over the life of the project (Pimentel et al. 2004). The total annual government subsidy is estimated to range from

\$2.5 billion to \$4.4 billion for the 4.5 million ha of irrigated land in the western United States (Myers and Kent 2001, van Beers and de Moor 2001). Worldwide, governmental water subsidies from 1994 to 1998 totaled \$45 billion per year for non-OECD (Organization for Economic Cooperation and Development) countries and \$15 billion for OECD countries (van Beers and de Moor 2001). During the same period, agricultural subsidies per year totaled \$65 billion for non-OECD countries and \$355 billion for OECD countries (van Beers and de Moor 2001).

According to the World Bank (2000), the objectives of fair water pricing are (a) to seek revenue to pay for the operations and maintenance of water availability, (b) to improve water-use efficiency, and (c) to recover the full costs of water pumping and treatment. However, 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 pricing problems (Schalch 2003).

If the prices of gasoline and diesel energy in the United States increase significantly, it follows that irrigation costs will also escalate from the current level of approximately \$3 billion per year (Pimentel et al. 2004). Since vegetable and fruit crops return more per dollar invested in irrigation water than field crops, farmers in countries with increased irrigation costs may need to reassess the crops they grow. For example, in Israel, 1000 L water from irrigation produces \$0.79 worth of groundnuts and \$0.57 worth of tomatoes, but only \$0.13 worth of corn grain and \$0.12 worth of wheat (Pimentel et al. 2004).

Loss of biodiversity. Natural diversity of species is essential to maintaining agriculture, forestry, and a productive environment for humans and other organisms. The water required to keep natural ecosystems, and especially plants, functioning has been appropriately termed *green water* (Falkenmark 1995).

Biodiversity throughout the world is adversely affected when water resources are reduced or polluted. Thus, the drastic drainage of more than half of US wetlands (Pimentel et al. 2004), which contain 45% of all 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 (Pimentel et al. 2004). Pear farmers in the Rogue Valley of Oregon use significant amounts of the river's water before it reaches Klamath Lake, leaving only 616 million m³ water per year for wildlife and other farmers downstream (Fattig 2001). Similarly, overpumping and upstream removal of water have reduced biodiversity in the Colorado River and the Rio Grande (Pimentel et al. 2004). The major alteration of the natural water flow in the lower US portion of the Colorado River has been responsible for 45 species of plants and animals being listed as federally endangered or threatened (Glenn et al. 2001).

Effects 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 and the accumulation of carbon dioxide, methane gas, and nitrous oxide in the atmosphere are projected to lead to global climate change. Over time, such changes may alter precipitation and temperature patterns throughout the world (Downing and Parry 1994, IPCC 2002). With major shifts in water availability, future agriculture, forestry, biodiversity, and diverse human activities will be affected. For example, if California experiences a 50% decrease in mountain snowpack because of global warming, as projected (Knowles and Cayan 2002), this will change both the timing and intensity of seasonal surface water flow (Pimentel et al. 2004). In contrast, Canada might benefit from the extended growing seasons caused by global warming, but even this region eventually could face water shortages (Parry and Carter 1989, IPCC 2002). If, as projected, the annual temperatures in the US Corn Belt rise by 3 to 4 degrees Celsius, rainfall may decline by about 10% (Myers and Kent 2001), and evaporation rates from the soil may increase, limiting corn production in the future (Pimentel et al. 2004).

The predicted global warming, along with increased human food requirements, can be expected to alter the amount of irrigation needed worldwide to ensure food security, probably increasing it by 30% (Doll 2002). Other serious impacts of global warming could include loss of biodiversity and increases in deforestation, desertification, and soil erosion. All of these major changes are likely to reduce water availability for humans and other living organisms, including the water needed for crop and forest production (Root et al. 2003).

Conflicts over water use

The rapid increase in freshwater withdrawals 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 water are due to the sharing of fresh water by countries and regions: There are currently 263 trans-boundary 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 for which data are available, the cost of conflicts related to the agricultural use of water was 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 fresh water from the Nile River, the second longest in the world, which is also shared by 10 other countries (Alavian 2003). Indeed, the Nile River is so overused that during parts of the year little or no fresh water reaches the Mediterranean Sea (Pimentel et al. 2004). Historically, the Middle East has

had more conflicts over water than any other region, largely because it has less available water per capita than most other regions, and all of its major rivers cross international borders (Gleick et al. 2002). Furthermore, the human populations in Middle Eastern 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 the water needs of several US states and between the needs of the United States and Mexico. Six states (California, Nevada, Colorado, New Mexico, Utah, and 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 the world's water must become a priority for 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 run off into streams and rivers. For example, the increased use of trees and shrubs makes it possible to catch and slow water runoff by 10% to 20%, thereby conserving water before it reaches streams, rivers, and lakes (Pimentel et al. 2004). This approach also reduces flooding.

Maintaining crop, livestock, and forest production requires conserving all of the water resources available, including rainfall. Some practical strategies that support water conservation for crop production include (a) monitoring soil water content; (b) adjusting water application needs to specific crops; (c) applying organic mulches to prevent water loss and improve water percolation by reducing water runoff and evaporation; (d) using crop rotations that reduce water runoff; (e) preventing the removal of biomass from land; (f) increasing the use of trees and shrubs to slow water runoff; and (g) employing precision irrigation with water delivery systems, such as drip irrigation, that result in efficient crop watering. In forest areas, humans should employ sound forest management and avoid clear-cutting. Trees can also benefit urban areas, where runoff rates are estimated to be 72% higher than in areas with forest cover (BASIN 2003). Moreover, runoff from roofs, driveways, roads, and parking lots is especially rapid; that water can be collected in cisterns and constructed ponds.

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

Using water wisely

Providing adequate quantities of pure, fresh water 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, 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 these regions, where groundwater resources are the primary sources of water, future agricultural, industrial, and urban water use must be carefully managed to prevent exhausting the aquifers.

We recommend the following priorities for using water wisely:

- Because agriculture consumes 70% of the world's fresh water, farmers should be the primary target for incentives to conserve water.
- Farmers should implement water-conserving irrigation practices, such as drip irrigation, to reduce water waste.
- Similarly, farmers should implement water and soil conservation practices, such as cover crops and crop rotations, to minimize rapid water runoff related to soil erosion.
- Governments should reduce or eliminate water subsidies that encourage the wasteful use of water by farmers, industry, and the public.
- Governments and private industry should implement World Bank (2003) policies for the fair pricing of fresh water.
- Policymakers and managers should protect forests, wetlands, and natural ecosystems to enhance the conservation of water.
- Governments and private industry should control water pollution to protect public health, agriculture, and the environment.

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