Chapter 7

Sustainable Water Management and Agriculture

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Introduction

Fresh water is a resource that is just as important to humanity today as it was in ancient times, when civilizations such as Egypt and Mesopotamia thrived because of their access to reliable supplies. But today the stresses placed on water supplies by a large global population with rapidly growing demands raise unprecedented challenges. The challenges are particularly important for agriculture, which consumes approximately 70% of water appropriated for human use.[1] Agricultural water supplies in many regions of the world are threatened both by unsustainable depletion and by degradation in quality. In this paper, we consider the role of water in agriculture and use a number of case studies to develop conclusions concerning long-term sustainable water resource management.

The Global Water Situation

Water is a renewable resource which is intercepted (or "appropriated") by man as it moves through the hydrologic cycle. This cycle, which is ultimately driven by solar energy, carries water from the atmosphere to the land and oceans and back again. The largest flux appropriated for human use is the portion of natural evapotranspiration emanating from harvested forests and dryland agriculture. The global long-term average is about 18.2 x 10^3 km^3/yr. This is about three times the annual flow of the Amazon river. Most of the remaining appropriations are for irrigated agriculture, industry, and domestic use, totaling about 4.4 x 10^3 km^3/yr (Global water budget data cited in this section are from Postel et al.[1] and Gleick[2]). These are satisfied primarily by direct withdrawals from "accessible runoff," defined as the accessible flux of water flowing from the land to the ocean as either river water or groundwater. The remainder is satisfied by nonrenewable extractions from water stored in lakes and ground water aquifers. Direct withdrawals account for about 35% of the current accessible runoff of 13 x 10^3 km^3/yr. If "instream water uses" such as navigation, maintenance of riparian ecosystems, and dilution of contamination are treated as claims on accessible runoff, this percentage increases to about 50%.

A global analysis provides useful context, but it only tells part of the story. Hydrologic fluxes vary greatly over time and space, and many regions use a much larger percentage of available water than the global average of 35-50%. An additional complication is the effect of water quality on accessible runoff. As water moves through the hydrologic cycle it picks up, transports, and deposits a wide range of substances, both natural and man-made, which influence its suitability for human uses. Domestic uses are typically the most demanding, since even trace amounts of certain contaminants can have adverse effects on human health. But, the suitability of water for industrial and agricultural uses is also dependent on the levels of solutes, especially salts, and on suspended sediment loads. In some areas, shortages can occur

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because poor quality renders a portion of accessible runoff unsuitable for particular uses. Although contaminants can usually be removed at the point of end use, this increases the cost of water, sometimes enough to make it unsuitable for price-sens- itive industrial or agricultural uses. In a sense, degraded water quality can be viewed as a depletion of accessible runoff. A variant on this theme is the concept that some portion of accessible runoff needs to be reserved to dilute natural and manmade wastes. As noted above, this has the effect of increasing the percentage of accessible runoff needed to satisfy human needs.

Spatial and temporal fluctuations in precipitation, evaporation, runoff, and water quality create regions of varying water abundance and scarcity. This has the effect of making water resource management a regional rather than a global enterprise. The spatial variability of water resources can be described in many ways. As a rough indication, it is revealing to note that the runoff available per capita varies from 300 m^3/yr in arid areas of Africa and Asia to 100,000 m^3/year in Canada.[2] This variability has serious implications for food production in arid and semi-arid regions which depend heavily on irrigation. Irrigated agriculture requires 1000 m^3/yr of diverted runoff to provide enough food to feed one adult for a year. Although only about 18% of all cropland is irrigated, irrigation accounts for 25% of all agricultural land in India, 35% in Indonesia and Iran, nearly 50% in China and Iraq, over 80% in Pakistan, and 100% in Egypt. In some of these areas there is simply not enough runoff to feed the local population. As a result, an undetermined (but probably large) fraction of irrigation water is obtained from unsustainable depletion of groundwater reserves. Once these reserves are exhausted, withdrawals will have to decrease.

Water shortages will also become more common in urban areas as populations grow and traditional supplies are jeopardized by degrading water quality. However, urban water users are in a better position to invest in conservation and treatment technology than subsistence farmers. To put the issue in perspective, the minimal amount of water required for domestic use is somewhat less than 10 m^3/person/year. This is typical of consumption levels in homes which lack running water. The global average domestic consumption level is about 50 m^3/person/year while per capita domestic water use in the United States is nearly 300 m^3/person/year. These wide ranges suggest that improved conservation and treatment technology could absorb much of the population-driven increase in urban water demand. The potential for urban water conservation is demonstrated both by the success of voluntary and imposed reductions in domestic use during droughts and by the substantial increase in water recycling by industrial users over the last few decades.

There is also room for water conservation in irrigated agriculture. Since most water withdrawals are used for irrigation, a small improvement in agricultural efficiency could provide enough extra water to satisfy growing urban demands. This argument has been convincingly applied to the California water situation, where large urban areas and productive agricultural regions compete for water from the same sources.[3] Although more efficient irrigation could resolve supply problems in some areas, it may have only a modest effect in others. This is because the improvements in efficiency which are technically and economically feasible may not be sufficient to satisfy the projected increase in demand, particularly in arid and semi-arid parts of the developing world. Improvements in irrigation efficiency require investments in expensive technology (e.g., drip irrigation). Commercial farmers can afford such investments only if their operations remain profitable. Subsistence farmers are generally dependent on free or low cost local sources, and have little or no cash to invest in more efficient technology. Also, there are inherent lower limits (other than plant evapotranspiration) on the amount of water required for productive cultivation of crops. One of the most important is related to the use of water for leaching salt from the root zone in situations where the applied irrigation water is moderately saline. If the irrigation is very efficient and all the applied water is taken up by the crop, salt will accumulate in the root zone and yield will eventually start to decline.

Our analysis of current and projected demands for water repeatedly reveals the critical role of irrigated agriculture in developing countries. Overall, we feel that the most serious problems of water scarcity and quality will be associated with food production in developing countries rather than with domestic and industrial use in urban areas. It will become increasingly difficult for arid and semi-arid regions in Africa and Asia to be self-sufficient in food production as their populations increase, their groundwater reserves are exhausted, and per capita runoff availability declines. This loss of self-sufficiency could be managed if:

1. Production in water rich areas of the major grain exporting countries (e.g., Canada and the United States) increases sufficiently; and
2. Local populations have the economic resources to buy food on the international market.

After all, many developed countries, even those with abundant water, are not self-sufficient in food but rely on imports to satisfy their needs. Although there is considerable room for expansion of production in the exporting countries, subsistence farmers in many arid regions do not have the cash income required to participate in the international grain market. In some developing countries, a sizable portion of the gross domestic product comes from vulnerable irrigated agriculture. The economies of these areas will have to change dramatically before their food needs can be met by imports.

We can anticipate that water problems will be especially serious in areas where:

1. Demands approach or exceed available fluxes;
2. Stress on limited water resources is degrading the quality of supplies; and
3. The population is highly dependent on food grown locally.

As the consequences of unsustainable depletion and degradation of water resources begin to be felt, current practices will inevitably have to change. The required changes may involve transitions from dependence on local subsistence agriculture to dependence on imports, investment in improved water resource infrastructure, adoption of new technologies, development of new policies which regulate depletion or insure that water is properly valued, or a combination of all of these. Careful planning and preparation will ease difficult transitions while maintaining food security and public health.

Important Water Resource Issues

In this section we examine some important issues related to the sustainability of current water practices, particularly those relevant to irrigated agriculture. Although these issues are generic, they are best illustrated with specific examples. In the end, global water problems are the sum of many regional and local problems such as those discussed here.

Groundwater Overdrafts

Consistently falling groundwater levels are an indicator of overexploitation. They are observed worldwide. In northern China,[4] western India[5] and South Africa,[6] groundwater tables are declining at rates between 1 and 3 m per year. The abstractions in the Sahara and Saudi Arabia deplete aquifers which since the last ice age have not had any recharge to speak of.[7] It is estimated that by 2010 the deeper aquifers of Saudi Arabia will have only 40% of their 1985 water reseryes left.[2] The present net depletion by overdraft of important groundwater reservoirs worldwide is at least 200 cubic kilometers per day.[8] In practically all cases, irrigation is responsible for overdrafts.

The best documented case of over pumping due to irrigation is the Ogallala aquifer in the Great Plains region of the United States. It is one of the largest aquifer systems in the world, stretching across parts of eight states, South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico and Texas, and underlying 174,000 square miles.

Groundwater withdrawal on a large scale started during the 1930 drought. Besides drought conditions, reasons for the fast development of groundwater irrigation were cheap energy, improved well drilling and pumping systems, and high crop prices. Development of groundwater resources for irrigation made this region one of the major agricultural regions in the United States. In the late 1970s, the abstraction rate of the Ogallala Aquifer amounted to more than a quarter of the groundwater used for irrigation in the US. Pumping rates many times in excess of the recharge rate led to a substantial decline in water levels ranging from 3 to 30 meters.[9] Up to 1990, the total abstraction exceeded the total recharge by 164 km^3.[10]

Water level declines were greatest in those parts of the aquifer where irrigation was developed first and where it was most intense. Severe depletion of the resource led to rising pumping costs, driving much of the irrigated agriculture in the region out of production by the early 1990s. In the Texas High Plains for example, irrigated area decreased by 34% between 1974 and 1989.[2] A large part of the area today has reverted to rainfed agriculture with much lower yields.

Increased pumping costs led to technical and institutional adaptations. Among the technical measures were increased irrigation efficiency and the practice of conservation tillage. Average water-use efficiency in the southern High Plains of Texas improved from about 50% in the mid-1970s to approximately 75% in 1990 due to improved technology. Current state of the art low pressure, full dropline center pivot systems are about 95% efficient. Buried drip lines approach 100% efficiency.[11] Institutional measures include groundwater laws that made possible the institution of regionally controlled groundwater management units, which set limits on the spacing and number of wells and carried out metering of water use and promotion of water conservation.[12]

Salinization

Salinization and related drainage problems are commonly associated with irrigated agriculture, especially in arid and semi-arid regions. In the dryland agriculture practiced in humid regions, most of the water in the crop root zone originates from rainfall, which has low salinity. The small amount of salt that enters the system is flushed through the root zone by the relatively large amount of excess water (water exceeding crop evapotranspiration and natural evaporation) available. By contrast, the water applied to irrigated crops is obtained from surface runoff, which picks up salts or gets more concentrated by evaporation as it flows over the land and into surface waters or subsurface aquifers. If all irrigation water is taken up by the crop (i.e., there is no excess), the salt contained in this water will accumulate in the root zone until the salinity reaches levels that will inhibit crop growth. If excess water is applied, as is usually the case, it will carry the salt through the root zone to deeper soil layers or, when the soil is highly impermeable, laterally to drainage ditches. If the water table is deeper than a few meters, the salt in the deeper soil layers will be transported downwards until it reaches groundwater. In many cases, the salt carried by groundwater later enters surface waters which may serve as irrigation sources for downstream users. If the water table is within a few meters of the ground, the salt held in soil moisture below the root zone during the growing season may be drawn upwards into the root zone by evaporation (capillary rise) during the fallow season. This salt must be leached out of the root zone during the next growing season or the salinity will eventually accumulate to harmful levels.

Since irrigation with slightly saline water requires, by its very nature, that water must be applied at levels exceeding crop evapotranspiration, it is important that the excess water (drainage) be removed from the crop system. Otherwise, it may raise groundwater levels and increase salt accumulation in the root zone. The problem of rising groundwater levels coupled with salinization is widespread in irrigated regions of the western United States, Asia, and our case study region in Australia. Although it is possible to install drainage systems which collect and divert much of the excess water used to leach salt, these systems can be expensive to construct and maintain. Furthermore, they just displace the problem of salt accumulation to another location (or user). Since the drainage water is more saline than the applied water, it is less desirable for irrigation. If the drainage water salinity is too high, this water must be treated as a waste product.

The scope and magnitude of irrigation-related salinization problems is well documented in Ghassemi et al.[5] An informative example is the Murray-Darling river basin located in southeastern Australia. This semi-arid basin covers about one-seventh of Australia and contains some of the continent's most productive agricultural land. It is distinguished by very low runoff (only one percent of precipitation) and high evapotranspiration. Salinization problems are important throughout the basin but have received particular attention in the lower Murrumbidgee River watershed, a 40,000 ha region planted predominantly in irrigated paddy rice, wine grapes, citrus, and dryland pasture. It is estimated that approximately 25% of cropland in the lower Murrumbidgee is slightly salinized while up to 15% is severely salinized. Moreover, the amount of affected land is increasing each year.

Annual rainfall in the lower watershed averages around 400 mm/yr, too little to support dryland cultivation of most food grains. Much of the irrigation water used to grow crops in this area is diverted from the Murrum- bidgee River, which rises in the more humid upland areas to the east. Irrigation related salinization problems in the Murrum- bidgee watershed are aggravated by the naturally high salinity of the shallow groundwater, which is within two meters of the surface over extensive sections of cropland, and by gradually increasing salt inflows to the river. These inflows are the result of agricultural drainage in the lowlands and dryland salinization (induced by deforestation) in the uplands.

In the Murrumbidgee watershed, artificial drainage systems are generally installed in fields planted to high value crops such as grapes and citrus. The effluent from these systems goes to downstream users in the watershed and then either to the Murrumbidgee River or to evaporation ponds. The paddy rice is generally grown on low permeability soils which permit the paddies to be flooded throughout the growing season. Much of the salt entering the paddies eventually leaves when they are drained at the end of the growing season. However, the recharge to groundwater is sufficient to have created extensive groundwater mounds beneath rice growing areas in the Murrumbidgee. The local water table rise has aggravated salinization due to capillary rise, especially in neighboring non-rice growing areas. Crops grown in these areas (especially grapes) generally cost more to grow than rice but consume less water and can be more profitable. As more salt accumulates in the root zone during the fallow season, more water must be used to flush the soil before planting. This puts further stress on the limited water supplies available for irrigation.

Rising water tables and associated problems of salinization have induced growers, government agencies, and other groups interested in the lower Murrumbidgee watershed to develop plans to insure that agriculture in the region can be sustained over the long term. The current plan specifies that rice can be grown only in rotation on approved land (with low infiltration rates), up to a limit of 30% of total farm area. However it is not clear either:

1. That these restrictions will insure that the region's agriculture is sustainable; or
2. That this is the most economically efficient way to achieve sustainability, particularly when external costs to downstream users and ecosystems are considered.

A study currently being carried out by the authors is examining both issues in more detail.

Sea Water Intrusion

In coastal areas over-exploitation of groundwater leads to seawater intrusion (see, e.g., SWIM'96).[13] Due to the density difference between fresh and saline water, a saltwater wedge forms naturally in coastal aquifers. If the freshwater flow is diminished by pumping, the wedge will proceed further inland, eventually leading to the contamination of wells. Wells which are screened in the freshwater layer may still draw salt by the phenomenon called upconing.[14,15]

At present, six out of ten people live within 60 km of a coast, and by the year 2000 more than two-thirds of the population of developing countries will live in the vicinity of the sea. The increasing concentration of human settlements in coastal areas gives rise to excessive pressure on groundwater resources, resulting in seawater intrusion and related deterioration of water quality.[16] Seawater intrusion is rampant along the coasts of India, Israel, southern China, Spain and Portugal, to name only a few.

In China, seawater intrusion has become more and more serious since 1970 in the eastern coastal zones. The following figures illustrate the situation on the Shandong coast, including the cities Laizhou, Weifang, Qingdao, Yantai, and Pingdu among others. The facts presented are taken from Wang et al.[17]

In the coastal area of Qingdao, Yantai and Weifang, the current water supply shortage in an average year is 3.1 km^3. Available water resources can only meet 60% of the total demand. In a dry year, the shortage is 5.1 km^3 or approximately 52% of the total demand. The well density rose from the original 10 wells/km^2 to 25 wells/km^2, and in some places even up to 70 wells/km^2. From 1976 to 1986, overabstraction caused a large groundwater level drawdown in the northern Weifang area. Up to now, the total area with groundwater levels lower than mean sea level is 2,400 km^2 in the Laizhou area. The lowest elevation is 20 m below sea level.

From Yantai City to Laizhou City, the area affected by seawater intrusion is up to 400 km^2 and growing fast. By the year 2000, the affected area will be 2000 km^2. The intrusion, which accelerated from a frontal speed of 46 m/yr to 400 m/yr between 1976 and 1988, caused serious damage to this area, in which around 450,000 people were affected. With growing salinity the soil productivity drops or may even be lost completely. About 80% of the cultivated land of the coastal plain of Laizhou City is affected and the grain loss is up to 75,000 tons per year.

To solve the problem, water resources management organizations were set up in Yantai City and water prices were increased, taking into account seasonal variation of scarcity. In order to save irrigation water, two measures were taken. First, drip irrigation and low pressure pump irrigation were introduced, which can save up to 90% and 30% of water, respectively. Second, earth canals were lined with concrete and open drains were replaced by pipes to decrease losses by evaporation and seepage.

The consequences of salinization are not seen all of a sudden, but progress gradually. Agriculture can adapt to a certain degree by planting more salt resistant, but usually less valuable, products. This happens on the Tamil Nadu coast in India, which is one of the most prominent examples for severe seawater intrusion. Rice cultivation has now given way to some more salt tolerant crops, such as trees for firewood. This allows the farmers to still procure income, but it does not reverse the trend of further degradation. Exploitation of groundwater with the help of electric and diesel pumps is continuing uncontrolled.[18] The main cause is the fact that electricity is free of charge for the villages and a change in this policy is virtually taboo. This shows the political and social dimensions of harnessing a problem which on the scientific side is well understood.

Nitrate Contamination

During the last few decades agricultural productivity has increased enough to keep pace with the rapid increase in global population. This dramatic increase in productivity is largely due to improvements in crop varieties and associated increases in the use of fertilizers and pesticides, technical innovations sometimes collectively referred to as the "Green revolution". The benefits of these innovations are apparent and relatively easy to document. What is not so apparent are the costs, both to human health and to the environment in general. Concerns about these costs have generated debates and have led to a number of regulations, especially in the developed countries. Many of the issues which arise in the case of fertilizer application can be illustrated with the case of nitrate use in Germany.

The increased use of nitrogen fertilizer for agriculture introduces additional nitrate into the biosphere. In order to put the issue in perspective, the nitrogen balance for Germany is summarized in Table 7.1.[19]

This table clearly reveals that the biological fixation of nitrogen is dwarfed by the inputs from nitrogen fertilizer and manure. On a global scale, nitrogen fixation associated with fertilizer production is already comparable to the total amount of natural (preindustrial) nitrogen fixation.[20] This means that the flux through the nitrogen cycle has been doubled by human activities. The harvesting of crops removes only little more than one-half of the total input. The remainder ends up in different compartments of the environment. (Table 7.2).

About one-third leaches into groundwater and eventually enriches surface waters before it gets back into the cycle in the form of nitrogen gas or is stored in the nitrogen pool of the soil. The ecological consequences of this intervention are still not fully understood. It is, however, well known that nitrogen enrichment increases the likelihood and extent of eutrophication, particularly in estuarine environments.

The denitrification which occurs in the aquifers under anaerobic conditions gets rid of nitrate, but utilizes resources such as organic carbon on the aquifer matrix which when used up is no longer available to maintain the aquifer function of denitrifying filtration. On the basis of a recharge rate in Germany of about 200 mm/yr and a maximum allowable concentration of 50 mg NO_3/l, and assuming that there is no denitrification, a maximum tolerable nitrate flux to groundwater of 20 kg N/ha/yr can be computed. The actual flux of nitrate to the groundwater with about 40 kg N/ha/yr is already twice as high.

The bulk of nitrate excess is due to intensive agriculture where the farmer fertilizes in the expectation of maximum yield. This yield is not achieved every year. In fact, in the majority of years the extraction of nitrogen with the crop will be less than the input of nitrogen by fertilization. Over the years, the accumulation of excess nitrate leads to a large pool of organically bound nitrogen in the soil, which makes the system more prone to produce episodically high temporary inputs of nitrate to groundwater by washout. A solution to this dilemma could come from precision agriculture, which monitors the soil's demands much more closely and makes it feasible to apply small amounts of fertilizer frequently in an economic fashion. The time required for such technical innovations to have an effect on the scale of nitrate concentrations could be quite large. This time includes the travel time in the unsaturated zone, the travel time in the saturated zone, and the time to deplete the pool of organically bound nitrogen in the topsoil. In a typical German watershed, this amounts to several decades

Table 7.1. Nitrate balance for Germany (1990)

	Units: kg N/(ha agricultural land)
Input	
Mineral fertilizer	135
N-fixation by legumes	14
Manure	78
Deposition from atmosphere	30
Sum	257
Output	
Withdrawal at harvest	141
Excess	**116**

The potentially adverse effects of nitrate on human health have been the primary focus of efforts to regulate nitrogen fertilizer use in Germany. The World Health Organization and the European Community have both adopted standards that require that nitrate concentrations in drinking water should not exceed a standard of 50 mg/l NO_3. Concentrations in excess of this value are found frequently in groundwater. In European countries such as Germany or Denmark, about 10% of all water works are above or close to this value. The fact that the percentage has been virtually constant over the last decade is misleading. It is not due to a leveling off of the problem, but rather to the continuous shutting down of polluted wells which then do not appear in the statistics any more. If one takes the "warning value" of 25

Table 7.2. Fate of nitrate excess (in %)

Total Nitrate Excess	kg N/ (ha agricultural land) = 100%
Direct surface runoff	9
Atmosphere as N_2O	5
Atmosphere as NH_3	18
N-pool of soil	17
Denitrification in soil	17
Leaching to groundwater	34

mg/l NO_3 as a threshold, the percentage of water works affected is almost twice as high. In the German State of Baden-Wuerttemberg, where an extensive monitoring program has been undertaken, regions with high concentrations show a leveling off, while formerly cleaner regions are still on the rise.

In Europe, non-point nitrate pollution of groundwater presents more of a problem than industrial pollution of groundwater. This is because the source is much more pervasive and the nitrate ion is very mobile and not easily removed by standard water processing techniques. Nitrate removal to meet existing standards could almost double present prices of drinking water in Germany. While such removal may be feasible in the centralized treatment plants of the industrialized world, it is much more difficult to implement in a cost effective way in the small decentralized water systems of the third world. As fertilizer use and domestic water demands increase in the developing world, it is quite possible that nitrate-induced health problems could become more pervasive. In the short term this will lead to increased costs, either for farmers who must reduce fertilizer application and accept lower yields, or for domestic water users, who must pay for nitrate removal. In the longer term, it may be possible to maintain high yields while reducing the amount of nitrogen leached into groundwater, e.g., through the use of "recession agriculture" or genetic manipulation of crops to provide for direct nitrogen fixation from the soil air.

Pesticide Contamination

Many of the issues encountered in the nitrate case study discussed above also arise with pesticides. The major differences lie in the nature of the human health and environmental costs incurred and in the types of technical solutions needed to reduce these costs. Also, the uncertainties associated with pesticide transport processes, and with the human health and ecological effects of pesticides, are probably even greater than the comparable uncertainties about nitrate.

By any measure used, whether volume applied, hectares treated or market value, global pesticide use is large and still increasing. In 1995, world consumption reached 2.6 million metric tons of so-called active ingredients (the biologically active compounds) with a market value of US $38 billion. About 75% of pesticide use occurs in developed countries, mostly in North America, Western Europe and Japan, where high pesticide application rates are common. In these countries, herbicide use dominates. Herbicides are generally less toxic than insecticides, which are more widely used in developing countries. In fact, pesticide applications in developing countries are growing steadily, especially where export crops such as cotton, bananas, coffee, vegetables and flowers are predominant.[21]

It is estimated that annual world consumption of herbicides was around 1 million tons in 1993. Arable land and permanent crops cover around 1.4 billion hectares worldwide. Assuming that between 80% and 85% of herbicides are for agricultural use and that they are distributed uniformly on cultivated land, an average of about 0.5 kg/ha is used every year.[22] However, local applications can be much higher in areas where intensive agriculture is practiced. Table 7.3 gives more location-specific figures on the average herbicide doses applied to corn, soybeans, rice, wheat and sugarbeets in the US (Illinois), France and Italy. These are well above the global average.

Cereals account for 0.7 billion ha, i.e., 50% of total global arable land, of which wheat, rice and corn are the most widespread. Among other crops, soybean is the most widely cultivated, with 56 million ha. This explains why more than 50% of herbicides are used on only a few crops.

Pesticides can move through the soil with water as it percolates down to groundwater. This process is called leaching. Both soil and pesticide properties must be considered when evaluating the tendency of a pesticide to leach in a particular location. The type of degradable organic matter (OM), the soil texture, and the soil acidity (pH) are the most important parameters determining the soil leaching potential, while the mobility, the persistence (usually given in terms of half-life), the rate of application and the application method are the relevant pesticide parameters. The strong heterogeneity of natural soils makes predictions of leaching potential difficult. Homogeneous soil column studies miss the most important point of pesticide transport in the field, which is preferential flow. Therefore, laboratory studies tend to underestimate the pollution potential of a pesticide.

The severity and global extent of groundwater contamination by pesticides cannot be adequately assessed. Data are only available in those isolated areas where monitoring programs have been carried out, i. e., almost exclusively in developed countries. The rapid introduction of pesticides into less developed countries has not been accompanied by monitoring, as the measurement of these compounds is still costly and requires a strong laboratory infrastructure.

Although pesticides can be removed from drinking water (e.g., with activated carbon), this becomes more difficult as the pesticide (or pesticide metabolites produced by biodegradation) becomes more polar. As with nitrate, the difficulties and expenses associated with removal fall more heavily on small water suppliers who do not benefit from economies of scale. Since most pesticide contamination comes from non-point sources, the effects can be widespread. When taken together, these two factors make pesticide contamination particularly problematic in agricultural regions, such as rural Denmark, where drinking water is obtained from many small suppliers.

Denmark's decentralized water supply system consists of 3,470 waterworks. A recent monitoring program examined pesticide concentration in groundwater samples from 976 monitoring wells and 2,798 abstraction wells.[26] This program revealed that 3 to 4% of the samples exceeded the maximum limit for individual pesticides in drinking water (0.1 μg/l). By way of comparison, in the same survey no samples of chlorinated hydrocarbons exceeded the comparable threshold (25 μg/l). In about 10 percent of the samples, one or more of a target group of eight pesticides were detected. These pesticides were found down to a depth of 60-70 m, most frequently in younger shallow groundwaters, with the occurrence generally decreasing with depth. The pesticides dichlorprop, mechlorprop (phenoxyacids) and atrazine (triazine) were most frequently found. Phenoxy acids have been found exclusively in anaerobic aquifers, often under bedded thick till and clay layers. In unconfined aerobic sand aquifers, triazines are found.[27]

Some of the Danish counties analyzed groundwater samples from monitoring wells for more than the 8 pesticides in the target group. These detailed studies revealed the presence of 35 pesticides or metabolites in Danish groundwater. Moreover, 22 of these were found with concentrations above the maximum admissible concentration in drinking water.[26] Understandably, these sampling results have been the source of great concern in Denmark, and wells with pesticide concentrations above the 0.1 μg/l threshold will be closed. It is worth noting that the threshold which prompted this action is based on historic detection limits rather than toxicological risk considerations.

In any case, it is likely that more Danish wells will be closed in the future, as nondegradable pesticides from more remote source areas arrive at additional pumping and monitoring sites. If this process continues, it is likely that Danish water supply system will have to become more centralized. In Denmark this does not necessarily pose a great problem, since water is plentiful and it is unlikely that pesticide contamination will create serious supply shortages. This may not be the case in more arid regions in developing countries, where localized treatment and centralization of water supplies may be technically difficult

Table 7.3. Average herbicide doses (g ha^{-1}) applied in different crops (1988)

	Corn	Soybeans	Rice	Wheat	Sugarbeets
Illinois (USA)	3125	1400	-	-	-
France	2000	1600-2480	-	1140	3300-3800
Italy	3090	-	6500	1500-4100	7210

Adapted from Catizone,[23] Fougeroux and Bourdet,[24] Pike et al.[25]

and/or may impose significant economic penalties on local populations.

Conclusions

Our analysis of the global water situation, as well as regional case studies such as those presented here, reveals the following general conclusions:

The critical water issues of the next few decades will be regional and basin-scale rather than global. However, regional issues will have global impacts through their collective effects on world trade, political conflict, and incentives for technological innovation.

The most serious problems of water scarcity will be associated with irrigated agriculture in developing countries where subsistence farming accounts for most of the local food supply. Although it may eventually be desirable for such regions to cut back on irrigated agriculture and import more food from more humid regions, this will require substantial changes in their economies. Domestic and industrial needs are a small fraction of agricultural water use and can be reduced even further with existing technology and proven conservation practices. While irrigated agriculture can certainly benefit from efficiency improvements, it is unlikely that these improvements will keep pace with increasing demands for food.

Water quality problems associated with fertilizer and pesticide application will remain serious in some regions, but will probably diminish in others as agricultural practices and products become more environmentally sensitive. The technology to reduce discharges of potentially harmful agricultural chemicals is already available and will continue to improve. The more serious problem will be allocation of the costs of using this technology.

Salinization is likely to become the dominant agricultural water quality problem in much of the world. In some cases, the direct and external costs of salinization will be too high to justify continuation of irrigated agriculture. In others, existing crops will have to be replaced by substitutes which are more salt tolerant or which are more amenable to salinity control.

Stresses imposed by unsustainable depletion or by degraded water quality may take effect gradually, over many years. In some areas, farmers may adapt to changing environmental conditions by changing crops, by accepting lower yields (and incomes), or by adopting new cultivation practices and technologies. Other parties, such as downstream users, may also adapt in various ways to water shortages and degraded water quality. In all of these cases, explicit and/or hidden costs can be expected to be incurred.

There is a real need for more reliable and scientifically defensible assessments of regional water issues and of the prospects for the future. Uncertainties in the magnitude and quality of water fluxes, stocks and demands at the regional level frequently lead to differing opinions about the nature, severity and cause of water problems. This can, in turn, lead to the adoption of inappropriate or counterproductive policies. Scientists, engineers and economists can all play a role in making the policy process better informed and more effective. This will help to insure that we can provide secure food supplies for an increasing population while protecting our water resources.

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