Major Problems in the Global Water-Food Nexus

David Seckler and Upali Amarasinghe

Abstract

This paper reports on recent research by the International Water Management Institute (IWMI) on the complex relationships and issues concerning water resources and food production on a global scale—what we call the global water-food nexus. One of the major findings of the research is that by 2025 one-third of the world's population will live in countries afflicted by physical water scarcity. This means that even with substantial increases in the efficiency and productivity of water use, these countries will not have sufficient water resources to satisfy minimum water requirements for domestic uses and meet industrial, environmental and agricultural demands for water. Since agriculture consumes by far the largest percentage of water, most of these countries will have to take water from agriculture, allocate it to the other sectors and rely on increased food imports to meet their needs. Another 45% of the world's population in 2025 will live in countries that can escape physical water scarcity only through large, and possibly environmentally destructive, investments to develop additional water resources.

There is no easy way out of the problem of water scarcity. Indeed, one of the tasks of this paper is to show the limitations as well as the potentials of such proposed solutions as increased water-use efficiency in agriculture, or rainfed agriculture, or small-scale dams and irrigation systems. These and other techniques can alleviate this problem even in the most severely stressed countries. Certainly, one of the most potent technologies for water conservation in agriculture lies outside the water field per se, in the field of crop breeding. By increasing yields, shortening the growing season, extending cropped area to cooler areas and producing more drought-tolerant plants, crop breeding has greatly increased the productivity of water used in agriculture. It is extremely important to focus agricultural research on scarcity problems in water-food nexus through collaboration among crop scientists and water specialists; and IWMI is shortly convening a workshop for exactly that purpose.

Major Problems in the Global Water-Food Nexus[i]

David Seckler and Upali Amarasinghe

Prophecy is a good line of business, but it is full of risks.

Mark Twain, *Following the Equator*

Introduction

Water and food are two of the basic necessities of life—and food production depends crucially on water. In this paper we provide some of the major results of research in the global water-food nexus, as we call it, by the International Water Management Institute (IWMI).

The paper is divided into two parts. Part I presents the state of global water scarcity by country in 1995 with projections up to 2025. It is found that fully one-third of the people of the world in 2025 will live in countries suffering absolute, physical water scarcity. That is, they do not have sufficient water resources to meet minimum domestic, agricultural and environmental needs even with full development and most productive utilization of their water resources. Another 45% of the people in 2025 will live in countries that have sufficient water resources to meet their minimum needs, but which will have to embark on extremely expensive and possibly environmentally harmful water development projects to actually utilize these resources. In short the water outlook for countries containing two-thirds of the world's 2025 population is grim.

Part II discusses some of the major issues underlying these estimates and projections, and examines various courses of action for alleviating the problems of water scarcity. Since agriculture consumes over 70% of the world's developed water supplies, it is clear that most of the progress in conserving water has to be in the agricultural sector. But this is not as easy as many people think. While the efficiency of water-use in agriculture is not as high as it could be, it is much higher than is commonly thought. Certainly, the greatest gains in the productivity of water in agriculture to date originate from outside of the water field *per se*, in crop science. By increasing the yield per unit of land, shortening the growing season, developing drought-resistant varieties and extending productive crop systems to cool areas, crop research has substantially increased the productivity of water used in agriculture. Much more research on this subject is needed, and IWMI is shortly convening a workshop of leading water and crop scientists to develop a plan of integrated research in this area. Several other areas of opportunity are discussed in the text. These range from the vast but generally illusive potential of rainfed agriculture, through small dams and water harvesting technologies, to increased water use efficiency through sprinkler, drip and other kinds of improved irrigation systems.

Part I. Global Water Scarcity 1995-2025

The estimates and projections of global water scarcity are done through IWMI's PODIUM model, which is designed to simulate alternative food and water scenarios of the future. The results presented here are based on what we call the *basic scenario*.

The basic scenario is rather optimistic. Within an overall framework of social, technical and economic feasibility, it relies on substantial investments and changes in policies, institutions and management systems intended to achieve four major objectives:

- Achieve an adequate level of per capita food consumption, partly through increased irrigation, to substantially reduce malnutrition and the most extreme forms of poverty.
- Provide sufficient water to the domestic and industrial sectors to meet basic needs and economic demands for water in 2025.
- Increase food security and rural income in countries where a large percentage of poor people depend on agriculture for their livelihoods through agricultural development and protection from excessive (and often highly subsidized) agricultural imports.
- Introduce and enforce strong policies and programs to increase water quality and support environmental uses of water.

Realizing these objectives requires three major actions in the field of water resources and irrigation management in water-scarce countries:

- Greatly increase the productivity of water resources use.
- After productivity is increased, there generally remains a need for substantial increases in the amount of developed water supplies.
- Water resources development must be done with substantially reduced social and environmental costs than in the past—and people must be willing to pay the increased financial costs this policy necessarily entails.

As shown in figure 1[1], we have grouped the major countries of the world into three basic categories of water scarcity.

- **Group I** (in red) represent countries that face *physical water scarcity* in 2025. This means that, even with the highest feasible efficiency and productivity of water use, these countries do *not have sufficient water resources* to meet their agricultural, domestic, industrial and environmental needs in 2025. Indeed, many of these countries cannot even meet their present needs. The only options available for these countries are to invest in expensive desalinization plants and/or

[1] Figure 1 is based on the results of a detailed study of 45 countries that represents a major regions of the world and over 80 percents of its population, and a less detail study of another 80 countries.

reduce the amount of water used in agriculture, transfer it to the other sectors and import more food.

- **Group II** (in yellow) represents countries that face economic water scarcity in 2025. These countries have sufficient water resources to meet 2025 needs but which will have to increase water supplies through additional storage, conveyance and regulation systems by 25 percent or more over 1995 levels to meet their 2025 needs. Many of these countries face severe *financial and development capacity* problems in meeting their water needs.

- **Group III** (in blue) consists of countries that have no physical water scarcity and that will need to develop less than 25 percent more water supplies to meet their 2025 needs. In most cases, this will not pose a substantial problem for them. In fact, several countries in this group could actually decrease their 2025 water supplies from 1995 levels because of increased water productivity.

- **The crosshatched** countries on this map are countries that are projected to import over 10 percent of their total cereal consumption in 2025. The correlation between this set of countries and Group I is clear—but, of course, there are many other reasons for food imports than water scarcity

The PODIUM model operates at the country level. Therefore, it generally ignores the substantial differences in water scarcity within countries at the levels of regions or river basins. For example, about one-half of the population of China lives in the wet region of southern China, mainly in the Yangtse basin, while the other one-half lives in the arid north, mainly in the Yellow river basin. This is also true of India, where about one-half of the population lives in the arid northwest and southeast, while the remaining one-half lives in fairly wet areas. Much the same is true of many other countries. A particularly vivid example is Mauritania, which is mostly desert but falls in Group II. The reason is that 90 percent of the total population live along the southern border- along the Senegal River. This geographic issue needs to be addressed in the future but for now, it is sufficient to say that we have ignored regional differences in the group classifications for all countries except India and China—because of their huge size in terms of population and water use. Figure 1 shows a rough picture of the regional differences in these two countries. IWMI plans to make further regional distinctions for countries, like Mexico, that have large regional disparities in water and agriculture (also see Alcamo, Henrichs, and Rosch 1999).

It is also important to understand that we have used substantially lower population projections in preparing these estimates than are normally used. The United Nations presents *High*, *Medium* and *Low* projections for 2025 (UN 1999). Almost no one now believes the High projections are relevant. Most people use the Medium projection. For reasons explained in Seckler and Rock 1995, we believe that the Low estimate is the best one. There are substantial differences between these projections. The Medium one projects a 38 percent increase in population over the period, to 7.8 billion people in 2025, whereas the Low one projects an increase of 28 percent, to 7.3 billion. However, in the spirit of compromise we have used the average of the Medium and the Low projections for 2025. A major consequence of these lower projections is that by 2040 population growth will have slowed virtually to zero. Thus, if the world can satisfy its food and water demand over the next 30 to 40 years, most of the problem will have been solved for the foreseeable future.

Summarizing Figure 1, including one-half of the population of India and China in each of Group I and Group II, it is projected that by 2025

- 33 percent of the population of 45 countries will be in Group1, with physical water scarcity.
- 45 percent of the population will have substantially underdeveloped water resources, requiring 25 percent or more development of additional water supplies.
- 22 percent of the population, mainly developed countries, will have little or no water scarcity.

Together, Groups I and II contain of 78 percent of the population in 2025. Of course, this does not mean that everyone in these countries will directly be experiencing water scarcity. As usual, the economically better off members of most countries will have enough water and food, while poor and weak people will suffer the major part of the burden.

Part II. Water and Food: Demand and Supply

Food Demand

While most of this paper is concerned with the supply side of the water-food nexus, supply is meaningless without considering demand. Thus this section briefly outlines some of the major issues in world food and, hence, water demand and their implications for water supply.

FAO provides excellent data on food production and consumption in the world, conveniently entered on a CD-ROM (FAO 1998). These data are used extensively in PODIUM and we are grateful to FAO for this and other data on agriculture and irrigation.

The IMPACT model of the International Food Policy Research Institute (IFPRI) provides projections of food demands for 16 major countries and 22 inter-country regions in 2025. PODIUM uses the food *demand* projections of the IMPACT model, adjusted for the population projection noted before (and much of the water part of the PODIUM has been incorporated into the IMPACT model). However, the food *supply* projections are done independently in PODIUM. PODIUM also provides a means for policy makers to change the projections of food demand in order to *target* the nutritional standards they wish to achieve for their countries in 2025. Once these targets are set, the model provides a means of testing the feasibility of these targets in terms of agricultural and water constraints and the actions needed to achieve the targets.

The single most important component of nutrition is calorie consumption per capita. The average for developing countries is around 2,200 kcal/person/day. With reasonably varied diets, if people satisfy their calorie requirements, they will also satisfy their requirements for protein, minerals and vitamins. A major exception to this rule is when a very high percentage of total calories are from rice, which is low in protein. Other exceptions occur with low vegetable consumption, which may cause vitamin and mineral deficiencies. But, on the whole, the principal target is adequate calorie consumption.

But even if the average calorie intake of a country is 2,200 kcal/capita/day, this is not enough to assure that everyone in the country is actually obtaining enough. People with relatively high incomes tend to over-consume calories, mainly from animal products. Therefore, it is necessary to get substantially higher average calorie consumption in a country to attempt to achieve the minimum for poor people. How much higher this amount must be is largely a function of the distribution of income in a country. As a rule of thumb, something in the range of 2,700–3,200 kcal/day is adequate for most countries to satisfy basic food needs, depending on the distribution of income and other factors in individual countries.

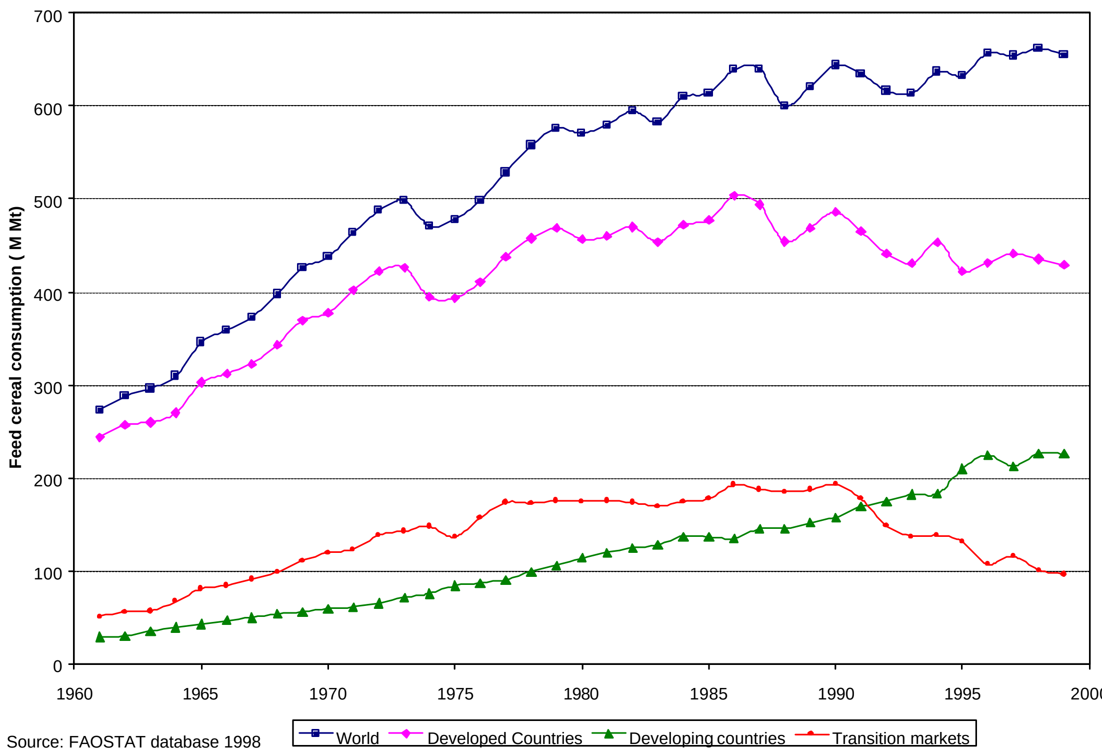
One of the most difficult issues in projecting the demand for food and related agricultural products in 2025 is consumption of animal products—meats, milk, cheese, etc. In most countries, the total calories consumed and the percentage of calories from animal products increase with income, even at high-income levels. However, because of a variety of causes including urbanization, health concerns and costs it is likely that there will be:

- a reduction in excessive per capita calorie consumption by higher-income groups ;
- a rapid growth in consumption per capita of meat products in developing countries, such as China and India, as incomes increase, combined with a tendency to plateau at lower levels of consumption than in the traditional meat-consuming countries of the west;
- a shift toward more vegetarian, or "Mediterranean," diets, away from meats; and
- a shift from red meats, notably beef, to white meats, notably chicken.

These changes on the food demand side will be accompanied by major changes on the food supply side. Traditional forms of animal husbandry produce most of the animal products in developing countries, where animal feeds are mainly from pastures and other lands not suitable for crops and from waste products. But the carrying capacity of these traditional feed resources is reaching its practical limit and most of the *additional* production of animal products will be from modern, commercial production units that depend on animal feeds (e.g., maize, barley, soybean meal, etc.). However, the carrying capacity of pastures in developing countries could be greatly increased with rotational grazing, better seeds and application of inorganic fertilizers (and this would increase the supply of organic fertilizers for crops).

Given the propensity to consume more animal products and the conversion from traditional to commercial production of these products, it is reasonable to assume that the production of feedstuffs will have to increase dramatically by 2025. However, it is a remarkable fact that while world consumption of animal products has increased rapidly, consumption of feed cereals has increased very slowly, at an annual rate of only 0.5 percent since 1985. Somehow, the world has received a "free lunch" in the production of animal products. Part of the reason for this is shown in figure 2. Developed countries barely increased consumption of feed cereals at all since 1985; developing countries nearly doubled their consumption from a comparatively small base, but this was offset by the decreased consumption in transitioning economies.

Figure 2. Total feed cereal domestic consumption.



Source: FAOSTAT database 1998

Underlying these data are changes in the production of animal products. Three important factors relating to the *conversion ratio*—the kg of feed required to produce one kg of animal products—have played an important role.

- The conversion ratios for red meats are about twice as high as those for white meats; thus, as consumption shifts from the former to the latter, feedstuffs are freed to produce more animal products.
- The conversion ratios of all animal products have been decreasing rapidly due to technological change in terms of animal breeding, health and nutrition. This frees up more feed to support additional consumption.

- There has been some substitution of feed cereals by other feeds, like oil meals and cassava.[2]

These factors all tend to decrease the conversion ratio for feed cereals. However, there is an offsetting factor. As developing countries move from traditional to commercial sources of feed for production, their incremental conversion ratios will *increase*. These effects have been incorporated in the analysis, conversion ratios decrease between 1995 and 2025 in most developed countries that are already under commercial forms of production of animal products, but, increase in most developing countries that have traditional forms of production.

It should be noted that the rapid growth in consumption of vegetables and fruits *increases* the demand for irrigation. The reason is that highly productive vegetable and fruit production is not possible without very good irrigation and drainage systems.

In sum, the demand for cereal grains is projected to increase by 37 percent in 2025, 49 percent of this increase is demand for feed grains. The demand for all food including cereals, fruits, vegetables etc. is projected to increase by 40 percent . After 2025, the rapidly decreasing growth of the world's population will make the task of meeting food demands much easier.

Water Supply: Irrigated and Rain-fed Agriculture

Irrigated agriculture has provided the base for the green revolution of the past forty years and, hence, the source of most of the growth in food production over this period. As the World Bank observes:

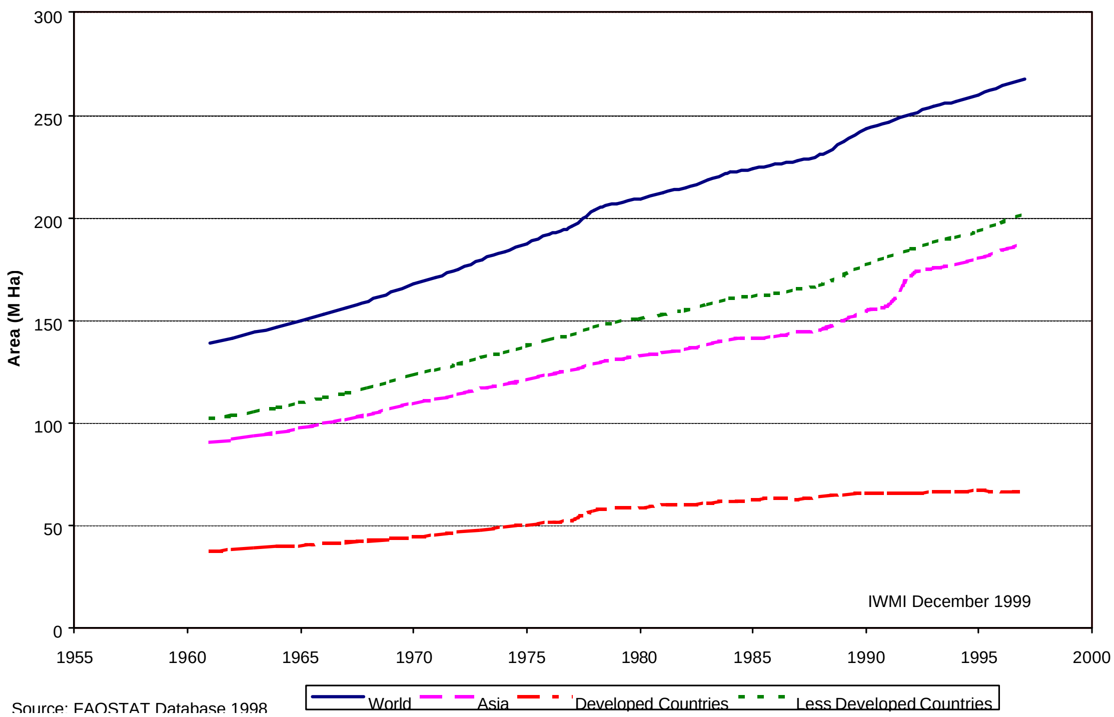
> Irrigated farmland provides 60 percent of the world's grain production. Of the near doubling of world grain production that took place between 1966 and 1990, irrigated land (working synergistically with high-yielding seed varieties and fertilizer) was responsible for 92 percent of the total. Irrigation is the key to developing high-value cash crops. By helping guarantee consistent production, irrigation spawns agro-industry. Finally, irrigation creates significant rural employment. The Bank has been a major actor in the expansion of irrigation systems… More than 46 million farming families have benefited directly from the Bank's irrigation activities.[3]

As shown in Figure 3, irrigated areas in the world have continued to expand at a fairly constant rate up to the present, with decreases in the growth rate in developed countries offset by increases in Asian and other developing countries. It should also be noted that the increase in gross irrigated area is probably even greater than indicated in figure 3 since the extent of multiple cropping on irrigated areas has expanded greatly-largely

[2]We are grateful to Alexandros Nicharos of FAO for pointing this out.
[3]Rural Development: From Vision to Action. 1997. Environmentally and Socially Sustainable Development Studies and Monographs Series 12.

through the use of tubewells in the dry season. This effect probably more than offsets the (uncounted) loss of irrigated areas due to urban sprawl, soil salinity and other factors.

Figure 3. Net irrigated area of the world, Asia, DCs and LDCs, 1961–1997.



However, virtually since large-scale irrigation development began, it has been attacked by critics who contend that in terms of costs, equity, environmental quality and even total food production, it would be better to invest in improved rainfed agriculture. The total cultivated area of the world is about one billion hectares, of which only about one-third is irrigated. Thus, a 10 percent increase in the productivity of rain-fed agriculture would have twice the impact as the same increase in irrigated agriculture. As the beneficial impact would be largely on poor farmers in marginal areas, this is an enormously attractive idea.

This is by no means a new idea. The goal of increasing productivity of marginal rain-fed areas has been energetically pursued, using all the tools of agronomic science, for at least a century, with generally disappointing results—especially in developing countries. We believe that the sciences and technologies of agronomy and water management have now advanced to the point where there are grounds for optimism in this field—and, indeed, there are notable cases of success on the ground. But, before solutions can be found, the depth and extent of the problems must be thoroughly understood.

A major part of the problem is shown in figure 4 (Hargreaves and Christiansen 1974). The vertical axis represents the relative yield; this is the actual yield obtained divided by the potential yield with all other factors such as seeds and fertilizers at their physically optimum levels. The horizontal axis shows the relative water supply; this is the actual water supplied divided by the physically optimal water supply.

While the amount of water that needs to be supplied to crops differs enormously among agroclimatic regions, most crops have nearly the same water requirement in the same agroclimatic region. This is because evaporation is by far the major determinant of crop water requirements. Thus the idea of conserving water by low water using crops is largely a myth. The exceptions are cool-weather crops such as barley, sugar-beets and winter wheat and very high-yielding crops, such as maize and potatoes, which produce more per unit area and time, thus per unit of water: more "crop per drop."

Figure 4. Moisture adequacy and yield function.

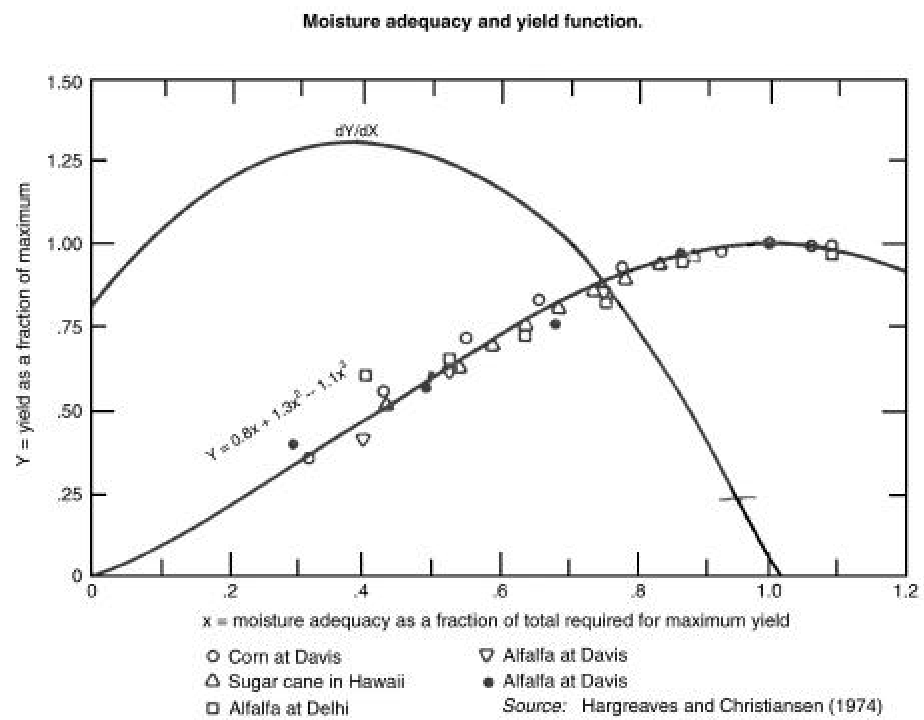


Figure 4 helps to explain the great diversity of rain-fed yields in the world. On the one hand, there are vast areas of the more favored rain-fed areas—such as parts of the American mid-west and north-central Europe—which have reasonably adequate and reliable water supplies and thus are close to the optimum conditions for high yields. But most of these favored areas have already been fully exploited. The lower one-third of the relative water supply axis unfortunately, characterizes most of the underdeveloped rain-fed areas of the world, where yields are 25 percent to 35 percent of potential. There here are also large areas of the world, indicated by the right-hand side of the yield curve, that suffer from too much water. Many of these areas can only grow rice. The combination of high humidity and temperature in these areas also contribute to the growth of plant and animal pests and diseases, which further reduce agricultural productivity. Masters and Webb 2000, for example, have found a significant positive correlation between agricultural productivity and the number of days of frost (which retards pests and diseases), up to a limit on days of frost.

These complications are graphically displayed in figure 5 (Droogers, Seckler and Makin 2001) which shows the maximum potential yield of crops in the world based on purely physical factors such as soils, precipitation, radiation and temperature. The maximum potential yield assumes ideal levels of inputs such as fertilizers and farm management and is thus unrealistic. But it provides an indicator of the physical constraints confronting farmers—and how, in some cases, farmers can overcome these constraints. Only a few of the more notable features of this figure are noted here.

- The north-central regions of South America appear to have vast and under exploited potential for growth of agricultural production. The same is true of the central region of Africa. However, diseases and pests are a major problem in many areas of Africa.
- The highly favored regions of Indonesia and parts of India and China are so because of the water tolerance of rice.
- The low to moderate potential of the American Midwest, combined with its high productivity, reflects the triumph of good farm management.
- Many productive but low potential—areas, such as the western parts of the USA and Canada and the USSR—show the importance of winter wheat, fallowing, and irrigation.

Certainly, figure 4 provides grounds for optimism on the potential for rainfed agriculture. But before substantial progress can be made in this field, the problems must be clearly understood. This discussion will concentrate on the dry end of the rainfed spectrum, on marginal rainfed areas. There are three central problems

- Most of a farmer's costs are the fixed costs of cultivating land *area*, independently of yield. Thus as yields decrease, net returns to farmers decrease even faster. For example, if costs represent 2 Metric tons per hectare (MT/ha), the farmer earns a net of 3 MT/ha at an economic maximum yield of 5 MT/ha, with optimal water supply. But the farmer makes only 1 MT/ha if yield is reduced to 3 MT/ha due to deficient water supply.
- In most cases, rainfall is highly unreliable. Farmers rationally minimize their investments in labor, improved seeds, fertilizers, soil and water management and the like to minimize losses due to drought. But this lack of investment in productive inputs means that even when good rainfall occurs, the yield is not as large as it should be.
- Since rainfall affects large areas, prices rise dramatically in times of drought, when there is nothing to sell and collapse in periods of good rainfall, when harvests exceed subsistence needs and there is a lot to sell.

These problems have been partly overcome in marginal rain-fed areas of developed countries such as the USA, Canada and Australia by large-scale, well-capitalized and highly mechanized farming. With several hundreds, if not thousands, of hectares per farm unit, large tractors and other equipment and sufficient capital to tide them over drought years, marginal rain-fed areas can be profitably farmed. Mechanization provides the ability to practice a variety of water and soil conservation practices—such as land leveling, terracing, fallowing, low-till agriculture, etc.—that are difficult and costly, if not altogether impossible, with only human and animal power. Because of their financial resources, these large farms can survive one out of three or four drought years. We believe that much of the future production of rain-fed farming in marginal areas will depend on the ability to bring these advantages of large-scale farming to small-scale producers through various methods of collective action (see Seckler 1992). But the history of such institutional innovations in developing countries has not been encouraging, to say the least.

It is hoped that advances in biotechnology will result in drought-resistant and more water-efficient crops. One problem with this idea is that, hitherto, drought-resistant crops and varieties are, for that very reason, low yielding. Such a crop may produce a more stable yield over varying climatic conditions but at such a low yield potential that it is uneconomical or unable to respond to favorable conditions.

However, *under specific agroclimatic conditions*, small-scale farming can be productive in marginal rain-fed areas through *supplemental irrigation*. Of course, all irrigation is supplemental irrigation because it is designed only to "top up" effective precipitation on the crops. But supplemental irrigation is a technique specifically designed for water-scarce regions, where scarce water is stored and used only in limited quantities at the critical growth stages of crops.

In many areas, for example, there is sufficient *average* rainfall over the crop season to obtain good yields, but yields are greatly reduced by short-term, 15- to 30-day, droughts at critical growth stages of the plant. Water stress at the flowering stage of maize, for example, will reduce yields by 60 percent, even if water is adequate during all the rest of the crop season. If there was a way to store *surplus water* before these critical stages and apply it if the rain fails in these critical stages, crop production would increase dramatically.

There are many ideas for water conservation and supplemental irrigation for smallholders. This is a long and complex subject that cannot be discussed at length here other than to say that often these ideas have failed in practice because of two important factors.

- They do not adequately consider the need to actually *have and store surplus water* before the drought episode.
- They fail to consider the economic costs, relative to benefits—which is all the farmer cares about.

One of the single most promising technologies in this field, that has gained wide adoption in India, is "percolation tanks." These are small reservoirs that capture runoff and hold the water for percolation into shallow water tables. The water is then pumped up onto fields when and only when, it is most needed. Groundwater storage avoids the high evaporation losses of surface storage; with pumps, the water table provides a cost-free water distribution system to farms; and percolation losses from irrigation are automatically captured by the water table for reuse. These percolation tanks can be combined with highly efficient sprinkler and drip irrigation conveyance systems to provide just the right amount of water when it is needed most.

In sum, it is likely that an *increasing proportion* of the world's food supply will have to be from irrigation. An important need is supplemental irrigation, in marginal rain-fed areas such as in sub-Saharan Africa, using advanced irrigation technologies. In fact, this absolutely has to happen if sub-Saharan Africa is to produce enough food to feed its rapidly growing population without an unacceptably high level of food dependence and provide remunerative rural employment.

Water Cycles and Water Use Efficiency

Water is the ultimately renewable resource. The amount of water on the planet has changed very little, if at all, since the earth formed some 20 billion years ago. This essentially fixed amount of water is in a perpetual state of cycling between the atmosphere and the surface and sub-surface areas of the globe. Water cycles between the atmosphere and the surface about seven times, so the actual quantum of water involved in total annual precipitation of the globe is only one-seventh of the total. The water cycle is extremely sensitive to temperature and such factors as plant cover, itself largely a product of the water cycle. Long-term changes in the distribution of water among its solid, liquid and vapor states, between fresh and saline water, and the geographic and temporal distribution of rainfall have had profound consequences to plant and, therefore, animal and human life on the planet. Global warming would exacerbate these natural fluctuations, with important but as yet unknown consequences to food production. But degree and duration of global warming is itself a matter of serious scientific debate. For example, S. Fred Singer, formerly Director of the United States Weather Satellite Service, says, "Surface thermometers report a warming trend, but weather satellites, providing the only true global data, show no atmospheric warming." (Wall Street Journal, Letters to the Editor, September 10, 2001)

Hydrologic cycles have a direct bearing on one of the central issues in the field of water scarcity—the issue of water use efficiency in agriculture and the other sectors. It is commonly thought that irrigation wastes enormous amounts of water. If we could just be more efficient with irrigation, more water would be available for all uses and we would not have to develop more water resources. Unfortunately, this perception is based on a misleading definition of water use efficiency (WUE).

WUE is broadly defined as the ratio of the amount of water required for a certain use (U) divided by the amount of water withdrawn or diverted (D) from a source—such as a river, aquifer, or reservoir—to serve that use: WUE = U/D. In irrigation, U is the amount of evapotranspiration (Eta) by crops minus the amount of water supplied by effective precipitation—or net evapotranspiration (NET). WUE can vary between 90% in the case of drip irrigation systems to as low as 20% in the case of paddy (rice) irrigation systems. But WUE is only a criterion of water delivery efficiency, it does not necessarily mean that water is lost, or wasted in low-efficiency systems. In order to know this we have to know what happens to the drainage water from the system. Drainage water is mainly from:

- seepage from conveyance systems,
- deep-percolation below the root-zone of plants in fields, and
- surface run-off from fields

Drainage water may flow to saline areas or the oceans where it is effectively lost to further human uses. In this case, increasing WUE (reducing drainage) *can result in real water savings*. On the other hand, drainage water may flow to other surface and sub-surface areas where it can be beneficially reused. This is the *return flow* of water, or water recycling. For example, surface flows of drainage from one field to another are characteristic means of irrigating paddy fields. It is obviously rather ridiculous to say that WUE is low, based on water delivered to only one field. But this same effect occurs, less obviously along river basins—with drainage water re-entering the river at one point and being diverted and reuse downstream. Drainage water is also a major source in the recharge of aquifers, where because of groundwater storage and timing, it may actually have a higher value than the surface water. Thus one person's drainage becomes another person's water supply. Under these conditions, attempts to increase WUE, usually at large cost, can easily result in a zero-sum game.

The concept of *basin efficiency* includes WUE and all these recycling effects. For example in Egypt, the typical WUE on a farm is only 40% to 50%. But for the Egyptian irrigation system as a whole, basin efficiency is close to 80%--and much of the remaining 20% is beneficially used in other sectors. The logic of water recycling may also be illustrated in the case of domestic water supplies in Egypt. Nearly all the water diverted and domestically used in Cairo returns to the Nile, from whence it is reused several times. But most of the water used in Alexandria flows to the sea, where it is lost to further uses.

While both the concepts of WUE and basin efficiency are valuable when properly understood and used, they are only physical concepts which must ultimately be used in a broader framework of analysis where the economic, environmental and social *value* of water is considered. This is the concept of *water productivity*. Water productivity can be increased by increasing yields per unit of water, or by allocating water from lower to higher valued crops—or, indeed, sometimes by allocating water from agriculture to other uses.

Esoteric as these concepts might appear to be they are of enormous practical importance. In the PODIUM model, for example, we project an increase in food production of 38% from irrigated agriculture with only a 17% increase in water diversions to agriculture. This effect is achieved by increases in WUE, in basin efficiency and in water productivity. And, as shown in a later section, recycling causes massive economic externalities in water management--and these externalities make it very difficult to price water rationally.

Groundwater Depletion

Another area of intensive competition for water and rapidly increasing water scarcity is the use of groundwater in irrigation. In terms of impact on food production, one of the greatest technical revolutions in irrigation has been the development of the small-scale pump. Tens of millions of small pumps are currently drawing water out of aquifers to irrigate crops. Over one-half of the irrigated area of India is now supplied by groundwater. Because pump irrigation provides water on demand, yields from pump irrigation can be two to three times those of canal irrigation. Since irrigation supplies about one-half of the total food production of India, one-third or more of India's food production depends on these humble devices and the aquifers that feed them.

Much the same is true in other arid countries. Yet, almost everywhere in the world, groundwater tables in areas that depend on irrigation from groundwater are falling at alarming rates. In many of the most pump-intensive areas of India and Pakistan, water tables are falling at rates of 2 to 3 meters per year. This is not surprising when one considers that the evaporation losses of a typical crop is around 0.5 m of depth and the yield of water in an aquifer is about 0.1 m per meter of depth. Without recharge, groundwater tables would fall by about 5 m per crop per year. Most of these areas receive sufficient average rainfall to recharge the aquifers, but most of the rainfall goes to runoff, not to recharge. We desperately need to change that relationship.

It is no exaggeration to say that the food security of India, Pakistan, China and many other countries in 2025 will largely depend on how they manage this groundwater problem. Reducing the amount of pump irrigation is no answer; this simply reduces the most productive agriculture. The answer has to be in groundwater recharge. But this is not an easy solution. Indeed, to our knowledge, no one has devised a cost-effective way to do it on the large scale required. About the only idea that we in IWMI have been able to think of is to encourage, through subsidies if necessary, flooded paddy (rice) cultivation in lands above the most threatened aquifers in the wet season. Paddy irrigation has high percolation losses and is thus a very inefficient form of irrigation from a traditional point of view. But from the point of view of groundwater recharge, this is just what the doctor ordered.[4]

Of course, one has to be careful not to pollute groundwater through leaching nitrates and other chemicals. Restrictions on fertilizer, pesticides and other chemicals in these recharge areas would be required. Ideally, the recharge areas would not be used for any other purpose—except, possibly fish production—but in densely population areas, land is too valuable to simply be set aside for this single use. IWMI and others are conducting research on ways of maximizing the rate of recharge and controlling pollution effects in this exceptionally important area of water resources management.

Competition for Water among the Agricultural, Urban, Industrial and Environmental Sectors

By 2025, most of the world's population will live in urban and peri-urban areas. The people and industries in these areas will demand an increasingly large share of the total water available and much of this will be taken from irrigated agriculture. Already, in India, the Philippines and many other countries, large irrigation areas are literally shut down, either permanently or in times of drought, by cities taking water from farmers, with no compensation paid to them for loss of their livelihoods.

Urbanization is creating an enormous pollution load on freshwater supplies and estuaries. The amount of pollutants thrown into the waterways is increasing rapidly and, at the same time, the flows of freshwater are decreasing as more water is evaporated through intensive use. Thus the *concentration* of pollutants is increasing even more rapidly than growth of urban populations and industries would indicate. It is only recently that we have begun to appreciate the economic value of waterways as waste disposal

[4]After this statement was written, attracting some criticisms from colleagues, we found that India has been doing precisely this in a 180,000-hectare area for the past 10 years. We will do a study of the results of this important project soon.

systems. As this previously free service ends and we have to treat water discharges, the costs will run to tens of billions of dollars. But the human health costs of the alternative of doing nothing would be even greater. Already, most vegetables grown in developing countries are irrigated with untreated sewage water from the nearby market towns.

As if this were not bad enough, most of the urban population will be concentrated in coastal areas where sewage water, whether treated or not, is discharged into the seas. In addition to the pollution problem, this greatly increases the consumptive use of water and prevents water recycling, thereby contributing disproportionately to water scarcity.

One of the most important although generally ignored water-using sectors is the environmental sector. More water is allocated in California to wetlands, free flowing rivers, estuaries and the like than to agriculture. The environmental sector has a strong impact on water scarcity because it can have high consumptive use. Exposed water surfaces evaporate rapidly and naturally flowing rivers generally end in the seas. This is a particularly acute problem in water-scarce developing countries. For example, the wetlands of the *Delta Central* on the Niger River in West Africa and the *Sud* on the White Nile in East Africa provide highly valuable wildlife sanctuaries and homes for migratory birds. But both of these wetlands evaporate around 50 percent of the water flow of their rivers. Both of these wetlands are under intensive pressure to redirect the water to lower evaporation losses and to provide water for human use downstream.

No one knows how large the water demands for the environmental sector actually are. Historically, water for this sector has been a naturally occurring free resource. But now that water is becoming more scarce, deliberate policies and water allocations to this sector have to be made. And it should be noted that, a decision not to develop water supplies for the other sectors on environmental grounds is a *de facto* allocation of water to the environmental sector. Here is another important area for future research.

International Trade in Food

Tony Allan (1998) has coined the valuable term “trade in virtual water” to show how international trade can help alleviate water scarcity and other problems in many countries. Countries with plentiful water should export water-intensive crops, like rice, to water-scarce countries. This is a natural application of the principle of comparative advantage in international trade. It happens today with rice, which is exported mainly from wet countries like Vietnam, Thailand and Myanmar and the USA (which has excess irrigation and food production capacity). Wheat is exported from Canada, the USA and Europe where it can be grown in cool seasons, with low-water requirements. Maize is exported from the USA largely because it can be grown without irrigation due to the exceptionally favorable agroclimatic conditions of the “corn belt.” This principle also pertains to trade within countries. Egypt could save nearly 10 percent of its scarce water supplies, for example, by replacing sugarcane production in the very hot south with cool season sugar beet production in the north.

Food imports are essential where countries cannot grow enough food because of water or other constraints, as in many countries of the Middle East and sub-Saharan Africa. This is also true for some countries in Southeast Asia, like Malaysia, where the expanding industrial and service sectors are creating severe labor resource constraints in agriculture. In some countries in sub-Saharan Africa, the costs of inland transportation make it better to feed coastal cities through imports than through domestic production—at least in the short term, until rural infrastructure can be created.

A major problem with trade, of course, is that food imports must be paid for in foreign exchange, earned from exports or by grants and loans. This fact is somewhat hidden by large amounts of donor assistance in hard currency and historically heavily subsidized exports from the USA and Europe. In the theory of comparative advantage, every country should be able to export enough to cover imports. But in practice, this does not happen. Many of the most needy countries, such as those of sub-Saharan Africa, do not have sufficient exports to pay for imports.

Economic consultants frequently have the revelation that water-scarce countries should devote their irrigation water only to high-valued crops, like flowers, fruits and vegetables, export them and then buy the cereals they need on international markets. A team from a famous American university recently found that the Middle East North African (MENA) countries would not have a water problem if they did this! The problem, of course, is that high-valued crops constitute very narrow and highly competitive markets, where only a modest increase in supply drives prices virtually to zero. Even within India, there are times when apples and potatoes are given away free in the producing regions. Every country, developing and developed, is already trying its best to produce and export high-valued crops.

Another advantage of international trade is that imports help to build local markets, tastes and skills that can result in new domestic industries through import substitution. For example, we expect a substantial shift toward import substitution in terms of domestic meat and feedgrain production in countries like India and China as local entrepreneurs catch up in these markets.

On the export side of the developed countries, it seems evident that there will be significant environmental and financial constraints on EU exports (we have heard that EU policy is to achieve self-sufficiency in food, but not to encourage food exports outside of the EU itself). In the USA and Canada, the ultimate results of the boom and bust cycles that the newly freed agricultural markets have been experiencing are not yet known, but they are currently encouraging an exodus from agriculture. Environmental pressures against irrigation and restoring water quality are also building in these countries.

The end result of these considerations is that we believe developing countries with a high percentage of their populations in rural areas will attempt to be as self-sufficient in agriculture as they reasonably can in order to conserve foreign exchange and provide rural livelihoods. They will gradually relax this objective over time as exports grow, the growth of the labor force slows and employment opportunities in other sectors improve. Of course, many countries cannot achieve this objective because of water and other constraints and will need to import considerably more food by 2025.

It appears that the production potential of the exporting countries will be sufficient to meet needs for increased cereal imports without severe financial or environmental damage. While the trade positions of many countries will change, net cereal exports, as a percentage of total cereal consumption in the world as a whole, will decrease from about 3.3 percent in 1995 to 1.8 percent in 2025. This means that total cereal exports of the countries will increase from 187 M Mt in 1995 to 224 M Mt in 2025.

Water Pricing and Institutions

It is one thing to estimate the potential for increased water productivity and quite another thing to achieve it. It is precisely because water is such an important economic good that, ironically, powerful forces do not want to treat it as such. As Mark Twain said, "Water flows uphill, toward power."

Some economists advocate pricing water at full marginal cost, both to achieve economic efficiency and to induce institutional change (see the discussion of these issues in Perry, Seckler, and Rock 1997). But water resources management is subject to failure of not only the public sector but also the private sector: in economic terms, it is subject to "market failure." Technically, water-recycling effects create massive external benefits and costs that violate the optimizing conditions of free market systems. The *intensity of external effects in water use is perhaps greater than in any other sector of the economy*; that is why water resources have always been a publicly managed or regulated resource.

There are many advantages to pricing water, if it is properly regulated. First and foremost, it provides a means of financing water service agencies and, since they are being paid by their clients, of holding their feet to the fire of performance. Second, entitlements to water provide a means of forcing compensation to users who are harmed by unregulated public and private systems. In many countries, water is being arbitrarily reallocated from farmers to cities (India and Philippines) and for environmental purposes (USA) with no compensation for the loss of livelihoods this creates. Entitlements to return flows also would force payment of compensation to downstream losers created by upstream changes in use (as, it appears, happens under the unregulated market system in Chile). Of course, as economists point out, pricing water can induce water use efficiency and allocative efficiency. But in many developing countries with hosts of small farmers to deal with, the transaction costs of marginal cost pricing are likely to be greater than the benefits.[5]

Pricing water is a good way to regulate the external *costs* of water use—for example, in water pollution. This is because the higher the price, the lesser the water that will be used and thus, other things remaining equal the lesser the pollution. But it is very difficult to regulate the external *benefits* of water use through pricing. For example, the external benefits of field-to-field irrigation in paddy systems, or the recharge of aquifers from irrigation systems would require a *negative price*, or subsidy, to reach the optimum level of water use. While this can and is being done, it is not usually considered by the advocates of (positive) water pricing—and all one can say is that this omission is evidence of poor economic training and analysis.

Socially, a minimum supply of safe water is one of the essentials of life and most people would agree that everyone should be entitled to receive that minimal amount. Market systems, on their own, may not have sufficient incentives to achieve that social objective; it depends on technical conditions of the demand and supply curves. But free water supplies to poor people have sometimes resulted in bankrupt water supply agencies, massive subsidies and preferred services to the rich.

Thus the introduction of water pricing and the need to manage water at the river-basin level means *more and better, not less, public management*. But a major problem in water

[5]C. J. Perry 1996, IWMI Research Report 2, page 22.

management in developing countries is the large and growing disparity between the remuneration of public and private sector staff. Bloated bureaucracies can only be supported by low wages. This inevitably leads to corruption and brain drains to the private sector—just as the needs for well-trained and dedicated people in the public sector are becoming increasingly acute. The first step in beginning the revolution in water management is to provide generous redundancy payments to marginal staff in public agencies, as a onetime write-off and then use the future savings to upgrade the civil service. The lessons of Hong Kong, Singapore and other countries where public servants are remunerated at rates comparable to the private sector indicate very high rates of return to such policies, if they are effectively implemented.

Given failure on both sides of the private-public table, it would appear that a partnership between the two is the only way out of the dilemma. There are innumerable experiments going on all over the world in designing and implementing these public-private sector partnerships. One of the most important research tasks for the future is to carefully and objectively monitor and evaluate these experiments so that everyone can learn from the experience. But until much more information is developed, it will remain exceptionally difficult to forecast the extent to which the potential gains in water productivity will become real gains.

Conclusion

We hope that this paper provides at least a glimpse at the many complex issues in the water-food nexus. To date, the world has had a comparatively easy ride on the back of generally ample water resources that only had to be developed to meet demands. But now, much of the world is simply running out of water—and much of the rest of the world is facing rapidly increasing financial and environmental costs of developing the water resources they have. The grounds for optimism are not in the supply side of the water-food nexus so much as in the demand side. Much of the world now consumes as much food as the need, or even want, and population growth is rapidly decelerating towards zero by the turn of the century. The world will require about 19% more water resource development by 2025. But after that big push is accomplished, normal improvements in water technology and management should carry us safely into the future.

References

Allan, T. 1998. *Moving water to satisfy uneven global needs: "Trading" water as an alternative to engineering it.* ICID Journal, 47(2):1-8

Alcamo, J., T. Henrichs, and T. Rosch 1999. *World water in 2025*. Global Modeling and scenario analysis for the World Commission on Water for the 21st Century (Unpublished report)

Droogers, P., David Seckler, and Ian Makin 2001, Estimating the Potential of Rain-fed Agriculture (Working Paper 21) Colombo, Sri Lanka: International Water Management Institute

FAO. 1998. FAOSTAT Statistical Database in CD-ROM, Rome: FAO

Hargreaves, G.H., and J. E. Christiansen, 1974. Production as a function of moisture availability. ITCC review vol. III No. 1(9). Association of Engineers and Architects in Israel: 179-189.

Perry, C. J., 1996. *Alternative Approaches to Cost Sharing for Water Services to Agriculture in Egypt.*, Research Report 2, Colombo, Sri Lanka: International Irrigation Management Institute

Perry, C. J., D. Seckler, and M. Rock 1997. *Water as an Economic Good: A solution, or a Problem?*, Research Report 14, Colombo, Sri Lanka: International Irrigation Management Institute.

Seckler, D. 1992. Irrigation policy, management and monitoring in developing countries. In Roundtable on Egyptian water policy: Conference Proceedings ed. M. Abu-Zeid, D. Seckler, Cairo: Water Research Center, Ministry of Public Works and Water Resources.

Seckler, David, and Michael Rock, 1995. *World population growth and food demand to 2025. Water resources and Irrigation Division*. Discussion Paper. Arlington Virgina, USA: Winrock International.

UN (United Nations), 1999. World Population Prospects, 1998 Revision. New York: UN Department for Policy Coordination and Sustainable Development.

Wall Street Journal, Letters to the Editor, September 10, 2001.

World Bank 1997. *From Vision to Action.* Environmentally and Socially Sustainable Development Studies and Monograph Series 12, Washington, D.C.: World Bank.

---

[i] **This paper is condensed and revised from a much more detailed treatment in "IWMI's Contribution to the World Water Vision," which can be found under "Other Research" on the IWMI web-site: www.iwmi.org.**