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The New Era of Water Resources Management: From "Dry" to "Wet" Water Savings

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DAVID SECKLER

CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH

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The World Bank, the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP) are Cosponsors of the CGIAR. The Chairman of the Group is a senior official of the World Bank, which provides the CGIAR System with a Secretariat in Washington, DC. The CGIAR is assisted by a Technical Advisory Committee, with a Secretariat at FAO in Rome.

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Introduction

Several months ago, I met with Mr. Ismail Serageldin, Vice President of the World Bank and Chairman of the Consultative Group on International Agricultural Research (CGIAR). In this meeting, he jolted me by saying that, in his judgment, water would be one of the major global issues of the twenty-first century. While I had always thought that water was important, I had not thought that it was *that* important. Considering the fact that the population of virtually all of the countries in Asia—with the notable exception of China—Africa, and the Middle East will double or triple in the next century, and that there are increasingly severe physical, economic, and environmental constraints on developing additional water supplies in these countries, I am now persuaded that Mr. Serageldin's statement is correct.

I believe, for example, that much of the social and political instability of Sub-Saharan Africa is due to the instability of its water regime and the consequent instability of food supplies and rural livelihoods. The Government of Egypt has publicly and repeatedly threatened to go to war, if necessary, to protect its supply of water in the Nile basin. Recently, an official of the Government of Sudan threatened to disrupt the supply of Nile water to Egypt by unstated means (*The Washington Post*, July 15, 1995, p. A18). The conflict over water rights is also exacerbating tensions between Palestinians and Israelis.

In yet another dimension of the problem, India's future food security depends crucially on the development of additional irrigated area. Indeed, over 70 percent of all of the additional food grain production in Asia as a whole since the beginning of the green revolution in the late 1960s has been on irrigated land. Yet India's largest irrigation project, the Sardar Sarovar Project in the Narmada water-basin, has encountered so much opposition from the environmental community that the World Bank has withheld funding for it. While there are valid social and environmental problems with this project, I am convinced that they can be managed and that international organizations should help India and other countries facing similar difficulties to manage them (Seckler 1992).

Globally, I am concerned that what may be called the "reserve food production capacity" of the world is decreasing, just as actual world food reserves are at historic lows. At the beginning of the green revolution, the gap between potential food production and actual food production increased to a historic high, largely because of the unrealized potential of high-yielding varieties (HYVs) and inorganic fertilizer, and the rapid expansion of irrigated area. Now, however, the gap is closing as the practical yield potential of HYVs is being reached in most countries due to high rates of fertilizer use, and the net growth of irrigated area in the world has probably become *negative.*

As investments in irrigation development decrease, as urban and industrial sprawl spreads over irrigated land, and as increasingly large amounts of water are diverted out of agriculture to these sectors and to serve environmental needs, both the area of irrigated land and the quality of irrigation necessarily decrease. All of these factors reduce the supply elasticity and the responsiveness of food production to random conjunctions of global events, mainly weather-related, that could create severe food shortages. Thus, with weather problems in the United States, Russia, and China, "analysts expect total world grain supplies to slip to 208 million metric tons next year—the smallest reservoir measured as a percentage of total use since the [United States] Government began tracking it in the 1960s" (*The Wall Street Journal,* July 11, 1995, p. A2).

Hence, part of what I mean by "the new era of water management" refers to the increasingly difficult problems in this field that the world will be facing in the future. In this phrase, I also want to emphasize the need to develop new and creative concepts in water management to adequately manage these problems. I believe that in order to arrive at solutions to problems, it is first necessary to define as precisely as possible what the problem is and is not. In Part I of this paper, I will attempt to define the generic problem of water management as I see it, and show that it is a much more severe problem than is commonly realized. Once we understand this problem clearly, we can avoid pursuing red herrings and focus our thinking on the kinds of creative and innovative devices that will lead to real solutions to the problem. That is the subject of Part II.

Part I: The Problem of Water Management

Waterbasins: Sources, Sinks, and Recycling

In order to fully understand the generic problem of water management, it is necessary to think in terms of waterbasins as a whole. There are several well-known facts about waterbasins that, considered together, lead to several rather surprising and counterintuitive conclusions about water resources management. The ecological concepts of sources, sinks, and recycling provide a useful means of understanding waterbasins (Seckler and Keller, in Abu-Zeid and Seckler, eds., 1992).

The sources of water in a basin are:

- Present precipitation, past precipitation—in the form of melting snow and ice—and surface and subsurface storage in reservoirs, lakes, the soil profile, and aquifers.

- Transbasin diversions from water-surplus to water-scarce basins.

- Desalinization of seawater.

With the exception of long-term climatic change, the average annual supply of water in a waterbasin from past and present precipitation is constant. Thus, unless there are technically and economically feasible opportunities for transbasin diversions or desalting seawater, the growth of population and economic activity in waterbasins means that water inevitably becomes more scarce relative to demand.

This problem becomes even more acute in light of the fact that the supply and demand for water vary dramatically by season. In the wet season, demand is low and supply is plentiful. The marginal value of water is zero or negative as most of the water floods out to salt sinks. In the dry season, the situation is reversed. Estimates and projections of average per capita water demand and supply conditions for countries, such as those by the World Resources Institute (1994), should be made in terms of the minimum dry season supply—not, as is usually the case, in terms of the average annual amounts.

The water sinks are:

- Losses of water vapor to the atmosphere through evaporation from surfaces and the evapotranspiration of plants.

- Surface and subsurface flows of usable water to salt sinks—oceans, inland seas, or saline aquifers.[1]

- Pollution of surface and subsurface water by salts and toxic elements to the point that the water becomes unusable.

One of the most important yet least appreciated facts about waterbasins is that there is a substantial amount of water recycling between sources and sinks. Because of recycling, it is helpful to think

1 Estuaries could be included as part of the waterbasin, and estuarian benefits could be counted as a beneficial use of water, but this complication is ignored here.

of water supply in terms of two distinct components. The primary water supply is from past and present precipitation, interbasin transfers, and seawater desalting. The secondary water supply derives from recycling the primary water supply.

When a unit of the primary water supply is *diverted* to a beneficial use, four important things happen to it:

1. Part of it is *evaporated* and is lost to the atmosphere.

2. The remainder is *drained* from the point of use to some other surface or subsurface place in the system.

3. Some amount of salt or other pollutants is picked up, or *absorbed* in the use of the water and carried in the drainage water.

4. The *concentration* of pollution in the drainage water increases both from the absorption of additional pollutants and evaporation losses from the diverted water.

As drainage water flows from a particular use, it may flow directly into a sink, such as direct discharge into a sea. Or, more commonly, it flows back into the surface or subsurface water system where it becomes a secondary source of supply.

The quality of the secondary supply of drainage water is always less than that of the primary water supply because water picks up pollutants as it is used, and because the consumptive use of water concentrates the pollutants that were in the input water. Thus, as water is progressively recycled through several stages in the waterbasin, the amount and concentration of pollutants in the water increase substantially.

On the other hand, if the polluted drainage water is blended with less polluted water, the pollution concentration of the total water supply decreases, and the water can become more usable even though the amount of pollutants in the two blended streams is the same. This is not true for highly toxic, nondegradable pollutants, such as heavy metals. However, saline drainage water from irrigated lands, for example, is often purposefully blended with less salty water so that it can be reused in irrigation. Similarly, treated drainage water from municipalities is blended back into the municipal supply stream for recycling. Many cities in the United States purposefully recycle a high percentage of their drainage—or treated sewage—water, including a deliberately vague amount used as drinking water.

Open and Closed Waterbasins

As population and economic activity increase in waterbasins, they evolve from an "open" to a "closed" state (Seckler 1992). In the beginning, in the open state, there is a sufficient supply of water to satisfy demand, even in the dry season, and primary water supplies of freshwater flow out of the basin into salt sinks. As growth continues in the basin, water supplies progressively tighten. Most of the primary supply is diverted to meet demand and an increasingly large percentage of drainage water is captured and reused. A progressively decreasing quantity of water, of diminishing quality, flows into the sinks in the dry season. Eventually, either all of the water has been evaporated upstream and there is no dry season flow into sinks at all, or the flow is so polluted that the water is not usable. At this point, the waterbasin becomes completely "closed," meaning, there is no usable water leaving the waterbasin.

A closed waterbasin can be reopened. In terms of annual supplies of water, it can be reopened by transbasin diversions and seawater desalinization. In terms of seasonal supplies, it can be reopened by intertemporal allocations of water from the wet season to the dry season through storage in reservoirs, aquifers, and the soil profile. However, these traditional "water development" techniques eventually reach the limits of economic and environmental viability and the waterbasins become permanently closed for all practical purposes. The Nile waterbasin, and many other waterbasins in the Middle East, are or soon will be permanently closed. The same is true of other major river basins in Asia.

As waterbasins approach closure, massive "headender-tailender" problems develop, with the tailenders at the bottom of the waterbasin receiving a progressively decreasing quantity of water of progressively diminishing quality. Over 20 percent of the world's population lives in urban conglomerations in coastal areas (World Resources Institute 1994), and a high percentage of the rural population and best agricultural lands are at the bottom of waterbasins. This can cause major problems; for example, studies indicate that the life expectancy of villagers around Lake Manzalla near the mouth of the Nile in Egypt is only 38 years because of water pollution. Rice is grown in this region of the Nile basin partly because it is one of the few crops that can tolerate the high salinity content of the irrigation water.

Local and Global Water Use Efficiency in Waterbasins

It is a well-known fact in the optimization theory that it is possible to obtain a "local optimum" position within a system that is suboptimal in terms of the system as a whole, at the level of the "global optimum." This can easily happen in waterbasins, especially in closed waterbasins. Since this is a complex and rather counterintuitive subject, it is best to begin with a simple example, or mental experiment.

According to an advertisement now running on television in the United States, if I turn off the water faucet when I brush my teeth, I will save 40 gallons of water each week. Similar water savings can be achieved by low-flow toilets and showers. Thus, through such simple devices, enormous quantities of water could be saved to meet future needs, thereby reducing or altogether eliminating the need for future water development projects.

This position, combined with water pricing and other incentives to induce water efficiency, represents a school of thought that advocates "demand management" in the field of water resources management, in opposition to the "supply management" approach of those who advocate water development projects.

Certainly, the position of demand management is valid in terms of local efficiency. In the above example, the same function, brushing teeth, is achieved with substantially—on the order of 90 percent—less water. Because of this gain in efficiency, substantially less water has to be diverted to serve tooth brushing functions and can be used to serve other needs. Also, as the number of tooth brushers increases, their demands can be met by the spread of increased efficiency among existing tooth brushers, without increasing the future supply of water for this purpose.

Is this position valid at the global level, in terms of higher water efficiency in the waterbasin as a whole? When water flows out of a faucet, it "goes down the drain." Since drains typically are pipe systems, there is little evaporative use of the drainage water. The drainage water disappears from view, but it does not disappear from the system. Because all of the local efficiency gains in this tooth brushing example are due to reducing drainage water, *the degree of global efficiency achieved by this water conservation technique depends crucially on what happened to the drainage water before the change.*

If, as is too often the case in sea resorts, for example, the drainage water from tooth brushing flows directly into the sea, then the practice of leaving the faucet on creates a "real" loss of water, and turning the faucet off creates a correspondingly "real" gain in water efficiency.[2] However if, as is more often the case, the drainage water flows back into the water supply and is captured and reused by downstream users, there is only an apparent, or "paper," gain in water efficiency. While diversions of water to tooth brushing uses decrease, and water is saved in this dimension, the secondary supply of drainage water also has decreased by the same amount so that the total water supply in the waterbasin remains the same.

This mental experiment provides a means of understanding the concept of water efficiency in greater depth. First, it shows the effect of "composition problems" in water resources management. What is

2 Direct drainage to the sea accounts for a large percentage of "real" water losses by the urban and industrial sectors. Since more than 20 percent of the world's population lives in coastal regions, it is very important from a water efficiency point of view.

true of all the parts is not necessarily true of the whole. There is nothing mysterious about this part-whole paradox, as proponents of "holistic" philosophy seem to think; it is simply due to interrelations among the parts, which create new phenomena, also called "scale effects" or "emergent properties," at the level of the whole (Seckler 1992; Keller, Keller, and Seckler 1995).

These effects may be briefly illustrated in the case of irrigated agriculture. Assume that a certain group of farmers, *A*, is applying 1,000 units of water to their land at 50 percent efficiency. This means that 500 units of the diverted water are beneficially used to meet the evapotranspiration requirements of the farmers' crops, while the other 500 units of the water are lost to these farmers' fields by surface and subsurface drainage. Assume that a second group of farmers, *B*, captures all the drainage water from *A* and applies it to their fields at 50 percent efficiency. Then 250 units of the drainage water are beneficially used to meet evapotranspiration requirements, while 250 units are lost to drainage. Now the overall global irrigation efficiency of the system, of *A* and *B* together, has increased to 500 + 250 or 750 units of water beneficially used, divided by the 1,000 units of initial supply, or 75 percent. Global efficiency would increase further if another group of farmers, *C*, used the drainage water from *B*, and so on.

Second, this example shows that in the new era of water management we must concentrate on achieving "real" not "paper" water savings; or, as they say in California, achieving "wet" not "dry" water savings. If a water conservation technique simply reduces the amount of drainage water from a particular use and this drainage water is beneficially used downstream, this would be only a "dry" water savings. However, if the drainage water flowed directly into a salt sink, this would be a "wet" water savings. In closed waterbasins, by definition, all of the usable drainage water is already being beneficially used; thus, water efficiency measures that only reduce drainage water create only "dry" water savings. In open systems, on the other hand, usable drainage water is being lost to salt sinks. Thus, reducing this loss by reducing drainage water will result in "wet" water savings—real gains in efficiency.

Keller and Keller (1995) have created an important new definition of "effective" irrigation efficiency that incorporates these recycling effects along with pollution effects. Willardson, Allen, and Frederiksen (1994) have recommended doing away with the term "irrigation efficiency" altogether in favor of an interesting approach based on various "fractions" of water. Frederiksen and Perry (1995) have applied the concept of "basin efficiency" to many cases around the world with important results for water resources analysis.

In sum, the real global gains in water efficiency achieved by reducing drainage losses depend on the state of the waterbasin, whether it is open or closed. However, this is only one source of efficiency gains. Whether in closed or open waterbasins, real efficiency gains can be achieved by:

- Increasing output per unit of evaporated water.
- Reducing water losses to sinks.
- Reducing the pollution of water.
- Reallocating water from lower valued to higher valued uses.

These four areas contain the set of opportunities for increasing the productivity of water in the new era of irrigation management.

Future Water Demand and Supply

One of the many important consequences of this new way of thinking about water resources in terms of the total waterbasin is that conventional estimates of water demand and supply—whether past, present, or future—become highly ambiguous. Most of the data are based on the diversions to the various sectors, with the sum total of diversions considered to be the aggregate demand for water. While this makes sense in certain contexts, it tells us nothing about water demand in relation to water supply. Since much of the water diverted is recycled, it becomes a secondary source of supply. Thus, it is very difficult to know what the supply and demand figures, presented in such publications as those of the World Resources Institute (1994), actually mean. Clearly, we need a concept of net diversions, or a *portmanteau* term that helps to distinguish between "wet" and "dry" water in our conversation, writing, and, most importantly, thinking.

For this reason, and with some trepidation, I propose to redefine the "consumptive use" of water to mean water that is lost to human use by *every* cause. Consumptive use, therefore, includes: (a) evaporative losses of water—its original meaning; (b) water lost to sinks; and (c) water rendered unusable because of pollution.

It is difficult to measure water losses due to pollution. If it is absolutely polluted, in the sense that it cannot be used at all, it is discharged to sinks and can be estimated as an addition to the usable water lost under (b). However if, as in the case of salt pollution below threshold levels of crops, it only reduces the productivity of water, there is only an economic, not a physical, measure of the amount of water involved.

In the case where pollution losses are due to concentration levels, as in the case of salt in irrigation water, one can follow the ingenious method of Keller and Keller (1995), and measure the physical amount of water lost to pollution from a particular use by the amount of fresh water that would be required to blend it back down to its original concentration of pollutants. This could be the basis of a pollution tax on water, for example, with the rate of tax being set at the marginal value of fresh water times the amount required to restore the drainage water to the quality of the diverted water. This would not work, of course, in the case of heavy metals or other toxic elements, which must simply be prohibited from entering the water stream. On the whole, this provides a reasonable, if rough, measure of the equivalent damage to water by ordinary forms of pollution.

With this definition, it is possible to discuss the *demand* for the *consumptive use* of various water sectors with conceptual clarity and then to measure the actual amounts of consumptive use. This would provide a measure of how much real "wet" water needs to be supplied to meet real "wet" water demands by sectors.

Future Water Demands

I would guess that the global demand for consumptive use of water has historically increased at a rate of about 2.0 percent per year, doubling every 35 years, and that over 80 percent of the total developed water in the world is consumptively used in irrigated agriculture. Thus, the demand for water is largely a function of the demand for food and, since most of the favorable rainfed areas have already been developed, of the demand for irrigated agriculture. Since population growth will be substantially lower in the future than it has been in the past, the growth in the demand for food and, therefore, the growth in the demand for water for irrigated agriculture will also be lower (Seckler 1993; Seckler 1994).

However, the urban and industrial demand for water is largely a function of the rate of economic growth, which is much higher in developing countries, especially in Asia, than it has been in the past. Already, as noted before, large amounts of water are being reallocated from the agricultural to the urban and industrial sectors, thereby lowering food production capacity, especially in developing countries. Fortunately, the consumptive use of water in the urban and industrial sectors is a much lower percentage of the water diverted to these sectors than it is in agriculture. Thus, with proper treatment and management, most of the drainage water from these sectors can be captured and reused. The greatest exception to this statement occurs in urban areas close to the seas where drainage water is simply dumped into sinks. Here the consumptive use of water can be very high, approaching 100 percent of the water diverted to these areas. Here is an important opportunity for real water savings.

The most rapidly growing and, in certain places, even the largest demand for water is from a sector that was not even explicitly recognized as such until a few years ago. This is the environmental sector. This sector demands water for preservation in its natural state, for maintenance of wildlife habitats, for aesthetic and recreational purposes, and similar uses. In California, for example, large amounts of water have been reallocated from agricultural uses to environmental uses, as well as to urban and industrial uses. Indeed, in terms of diversions of water, the environmental sector is now the single largest user of water in California, using 45 percent of the total water demand of the state, compared to 42 percent for agriculture (Department of Water Resources, State of California 1994), which leaves only 8 percent for the other sectors.

Unfortunately, the environmental sector also can be a high consumptive user of water because of large shallow surfaces of water exposed to evaporation in rivers, lakes, and wetlands and naturally flowing streams that discharge into sinks. It is estimated, for example, that fully 50 percent of the water in the Niger River is lost to evaporation in the vast wetlands below Timbuktu in Mali. These wetlands provide a valuable sanctuary for migratory birds and other wildlife. It is questionable if this parched region of the world will be able to sustain such a highly consumptive use of water for environmental purposes in the future.

In terms of the political economy of water, it may be noted that, while the demand for water from other sectors generally expresses itself in terms of increasing the supply of water through water development projects, environmental demands are generally expressed in terms of preserving water in its natural state, against water projects. The political power of the environmental sector assures that developing additional supplies of water to meet increasing demands, including environmental demands, will become more difficult in the future. As it is rightly said, "water runs uphill: toward power."

Part II: Increasing the Productivity of Water

This part of the paper focuses on specific techniques for increasing the productivity of water in irrigated agriculture. It is best to begin the discussion of irrigated agriculture with a brief review of the basic principles of irrigation.

The evaporative use of water in irrigated agriculture is partly due to the evaporation of water from exposed surface areas of water in the irrigation and drainage canal systems and on the surface of fields, but it is mainly due to the evaporative requirements, or evapotranspiration, of plants.

The rate of evaporation is determined mainly by "potential evapotranspiration" (*Eto*), which is a function of the climatic conditions of a region at a point of time—mainly heat, wind, and humidity. *Eto* can be approximated by the rate of evaporation from an open pan of water. The actual evapotranspiration of crops (*Eta*) varies somewhat among crops at various stages of growth. The specific crop coefficients are multiplied by *Eto* to obtain *Eta*. The table below shows the seasonal crop coefficients of some major crops under the *same Eto conditions.*

Table 1. Seasonal Crop Coefficients

Crop	Conditions Moist[a]	Dry[b]	Crop	Conditions Moist[a]	Dry[b]
Olive	0.40	0.60	Sugar Beet	0.80	0.90
Safflower	0.65	0.70	Citrus *(weeds)*	0.85	0.90
Grape	0.55	0.75	Cotton	0.80	0.90
Citrus *(no weeds)*	0.65	0.75	Green Bean	0.85	0.90
Fresh Pepper	0.70	0.80	Wheat	0.80	0.90
Groundnut	0.75	0.80	Dry Onion	0.80	0.90
Green Onion	0.65	0.80	Grain Maize	0.75	0.90
Cabbage	0.70	0.80	Tobacco	0.85	0.95
Dry Bean	0.70	0.80	Potato	0.75	0.95
Tropical Banana	0.70	0.80	Fresh Pea	0.80	0.95
Sunflower	0.75	0.85	Sweet Maize	0.80	0.95
Watermelon	0.75	0.85	Sugarcane	0.85	1.05
Sorghum	0.75	0.85	Alfalfa	0.85	1.05
Tomato	0.75	0.90	Rice	1.05	1.20
Soybean	0.75	0.90			

[a] High humidity ($RH_{min} > 70\%$) and low wind ($\mu < 5$ m/s).
[b] Low humidity ($RH_{min} < 20\%$) and strong wind ($\mu > 5$ m/s).

Source: Hargreaves and Samani (1986).

One of the curious things about irrigation is that while *Eta* is "bad" in the sense that water vapor is lost to the atmosphere, it is "good" because that is exactly what crops need water for. Less than one percent of the water consumed by crops is used for fluids in the plant, the rest is used to control the heat of the plant. Plants transpire for the same reason that people and some animals perspire: to dissipate heat through evaporation.

This mixture of good and bad in *Eta* creates several problems in trying to improve the productivity of irrigation by reducing consumptive use. For example, it is commonly thought that the consumptive use of water can be reduced by substituting crops with high *Eta* by crops with low *Eta*. There are two problems with this view. First, as shown in Table 1, there is not a great deal of difference in *Eta* among major crops *under the same Eto conditions*. Second, crop yields and *Eta* are highly correlated. This is because the same factor, radiant energy, drives both yield and, through heat, *Eta*, under favorable conditions of water, fertilizer, and other inputs. This is a classic case of statistical multicolinearity, although the evaporation and radiant energy correlation may differ by climatic factors, such as clouds and wind.

Thus, while it is generally true that wheat consumes substantially less water per unit of yield than does rice, and sugar beet less than sugarcane, the reason is not *Eta*, but *Eto*. Wheat and sugar beet are cool weather crops, while rice is largely grown in the hot season, when *Eto* is high, and sugarcane, with a twelve- to eighteen-month growing season, grows through the hot season. *The interseasonal and interregional variation in Eto is much larger than the intercrop variation in Eta.*

Thus, in regions where water is scarce in the hot season, large savings in the consumptive use of water can be achieved by substituting crops grown in the hot season by crops grown in the cool season, so long as radiant energy and yield remain roughly the same.[3] Also, large

[3] However, in much of the tropics, the hot season corresponds with high precipitation. Because of the ability to capture precipitation in rice fields, rice can be a highly water-efficient crop in the hot, wet season.

savings could be achieved by moving crop production from high *Eto* regions to low *Eto* regions; for example, out of windy regions to more tranquil regions. It should also be noted that most trees are heavy evaporative consumers of water because of the large exposed surface area of the leaves and their height, which place them—like wind energy devices—up where wind speeds can be several times that at ground level.

Studies of the crop systems of the Nile basin below the High Aswan Dam, for example, show that about 10 percent of the total consumptive use of the water in the system could be saved if crops were not grown in the hot, windy season of the upper Nile around Luxor, but were grown lower in the Nile where it is cooler with less severe winds. The farmers could be paid not to grow crops during that period, just as they are paid not to grow crops in the United States and Europe under land retirement plans. This means that they would be paid not to grow sugarcane at all.

Here is a major challenge to agricultural research and plant breeders, to develop more cool season varieties of crops, like wheat, barley, and sugar beet. Better cool weather maize varieties, for example, would be very helpful, as would a nine-month variety of sugarcane. Also, if possible, it would be valuable to find economical plant species and varieties that have lower *Eta* in hot, windy regimes, like olive in Table 1. Are there valuable plants that shut down, like cactus, when the heat, and wind, are on?

A substantial loss in water productivity is due to the lack of reliability of irrigation water in surface irrigation systems. Water is applied, and consumptively used, to start the crop, but then one or two irrigation turns are missed, sometimes at a critical growth stage of the crop, and yields are reduced substantially below what they should be, especially in the tails of the system. Part of this problem is due to mismanagement, part is due to "surge" effects in the supply of water to the irrigation system. This problem can be solved by standby tubewells along the distribution channels to provide supplementary irrigation in times of temporary shortage.

The problems of water distribution and unreliability of supply are particularly acute in the use of drainage water. Most of the drainage water enters the irrigation management system as secondary surface and subsurface supply. A substantial amount of drainage water is simply discharged to local sinks in an unmanaged way. If the quality of the drainage water is good and these are not salt sinks, this water can be used for irrigation. Much of the irrigated area of rice and hemp is accidentally irrigated by this means. However, if these are salt sinks, the drainage water creates waterlogging and salinity problems. Similarly, good quality drainage water is often dumped into the sea, for lack of proper attention and management. One of the major tasks of the new era is to actively manage drainage water as secondary supply. In many waterbasins, this is virtually the only surplus "wet" water there is.

On this subject, an intriguing conjecture may be noted. The *Eta* requirements of crops increase with yields, although the exact nature of this relationship is not altogether clear. Thus, since yields in most irrigated areas have increased substantially over the past few decades, evapotranspiration should also have increased. If this is true, then the irrigated areas are becoming relatively more stressed for water. This may account for part of the widely held view that irrigation systems are now performing worse—for example, with more tailender problems—than they have in the past. If so, again, these systems need more water inputs.

These considerations lead to several policy issues that deserve serious thought. One is to decrease the variability of water supply through better conjunctive use of water—with deliberate overirrigation in times of surplus to recharge aquifers—and pumping into the canal systems, as well as from private tubewells. Another way to increase water supply is to reduce evaporative losses in the watersheds by replacing some trees with grasses, which would also reduce soil erosion. Barring additional water inputs to irrigation systems, water productivity may be increased by consolidating the area, with more reliable water supplies to less irrigated area. However, this would seriously disturb the distribution of benefits of irrigation. Clearly, such alternatives need to be carefully studied under specific conditions of time and place before decisions are made.

Another source of real water savings is better management of fallow land (Perry 1995). Even barren land will evaporate water through capillary action down to a depth of two meters. The draw on shallow water tables and replenishing soil moisture in the soil profile can amount to a substantial loss. Perry (1995) estimates that in the Nile basin below the High Aswan Dam as much as 3 billion cubic meters of water—7 percent of the total supply to irrigation—are evaporated because of this factor. Also, in most developing countries, weeds are permitted to grow on fallow land. This not only assures a supply of weed seeds for the next crop, but the weeds pump out the subsurface moisture and mine high water tables. If fallow lands are kept barren and a "dust mulch" of loose soil on the surface is maintained, the soil moisture is retained.

In thinking about reducing evapotranspiration in irrigated agriculture, the "evapo" part should be separated from the "transpiration" part. While it may be possible to develop more heat-resistant and, therefore, less-transpiring plants, this would appear to be an exceptionally difficult task. The "evapo" part, which is due to the evaporation of moisture in fields, is easier to control. As shown in Table 1, most of the difference in *Eta* between rice and other crops is in the planting season because of high evaporation losses before the crop cover is established. A study by the International Irrigation Management Institute (IIMI) of dry seeding rice in the Muda Irrigation Project in Malaysia showed water savings of 25 percent by eliminating pretransplanting flooding of rice fields. Some of this was probably "paper" water savings of drainage water, but some of it was undoubtedly "real" water savings of evaporation losses. Studies of planting sprouted rice seeds by the International Rice Research Institute (IRRI) have shown similar results (Bhuiyan, Sattar, and Khan 1994). Interestingly, farmers are adapting these water saving techniques, not to save water, but to save the high labor costs of transplanting rice.

Field evaporation losses can also be reduced by drip and trickle irrigation systems, which apply water directly to the root zone of the crop in correspondence with *Eta.* This is not so true of sprinkler irrigation systems, however. Throwing fine particles of water through hot air is about the best way to maximize evaporation losses. The common belief that sprinkler systems are water efficient is due to their high uniformity of water application, which lowers drainage water losses, which may be only "paper" savings. However, modern, downward sprinkling systems substantially reduce evaporation losses.

In areas that have good, salt-free water soils, subirrigation can be a highly productive form of irrigation. By putting barrages in rivers, water tables can be raised to the root zone of plants. This provides irrigation with less evaporation, together with a considerable amount of subsurface water storage. A substantial although unknown part of the *Eta* of crops in Egypt is met through subirrigation. This is also true in Indonesian rice fields where stream barrages also lower drainage losses in the fields by creating high water tables.

In areas that do have water salinity problems, the productivity of water can be substantially increased by carefully controlling the application of irrigation water through sprinklers and other forms of pressurized (pipe-based) water application systems. Combined with tubewells, these systems can lower water tables and be used to drive salts below the root zone of plants, where they can be permanently stored in a harmless state. This may be the only real solution to the salinity problems of Pakistan and other saline areas of the world that do not have good drainage to the sea.

There has been promising research in developing commercially valuable halophytes—salt-tolerant plants. [I am grateful to Jack Keller for this suggestion.] In California, for example, salty drainage water from a normal crop is captured and used to irrigate cotton, which is highly tolerant to salt. Then the drainage water from the cotton, which now has high salt concentration, is used to irrigate halophytes. Then the drainage water from the halophytes, which may have a higher salt concentration than seawater, is pumped into evaporation ponds. After evaporation, the salt residue is scraped up and transported by truck or train out of the system. Indeed, the salt may be sold to commercial users. Here is another technique for salt control that should be thoroughly investigated.

Turning to the economic dimensions of the problem, it is clear that the productivity of water can be increased by substituting crops with low economic value per unit of water consumptively used with crops with high value. While this is valid in principle, it may not be as easy as it seems. Since the consumptive use of water by crops is largely a function of *Eto*, not *Eta*, there is not much difference in the consumptive use of crops in the same season and crop substitutions must occur in the same season of the crop calendar. Otherwise, the land and other factors of production are idle. If the net value of a crop in the same season is in fact higher than that of another crop in that season, it is likely that the farmers would already have made the substitution.

In closed water systems, the quality of water is as important as the quantity of water in determining ultimately usable supply. There is no question that excessive amounts of fertilizer—whether organic or inorganic—are used in some of the major river basins, and that the salts from these fertilizers substantially reduce the quality of water. In such cases, reducing fertilizer use by such means as a tax on fertilizers may be appropriate.

Lastly, at the global level, it is clear that, as water becomes progressively more scarce in the major crop producing nations, international trade in agricultural commodities will increasingly be determined by the amount of water required to produce crops—their "water content"—in relation to the relative water supplies of trading nations. This will give even greater comparative advantages to the favorable rainfed areas of Europe, North America, and parts of South America. Production of hot season crops like sugarcane, summer rice, and maize will concentrate in high water availability areas. Carruthers (1993) contends that, in the future, the Asian nations will become the greatest exporters of industrial products while the western nations will specialize in food exports. The economic logic of water lends support to that hypothesis. Recent food demand and supply studies (Agcaoili and Rosegrant 1995), for example, project that international trade in cereals will roughly double by 2010, and that virtually all of the increased trade will be in the form of exports from North America and Europe to Asia.

However, these international water trading ideas depend crucially on the ability of countries to finance food imports, on infrastructural investments in irrigation, transport, and other facilities, and on the global supply and distribution of water. If all of the agriculturally productive waterbasins in the world are encountering water scarcities, then, obviously, the scope of international trade in high water content agricultural commodities will be restricted.

Conclusion

There is much that can be done to improve the productivity of water on technical grounds. The institutional, social, and economic aspects of these improvements need to be carefully investigated to determine the feasibility of these improvements. Given the fact that existing irrigation and other water-using systems are not nearly as inefficient as they are commonly thought to be at the level of global efficiency, there will remain a need for further water development projects. This will require better conjunctive use of surface and subsurface water supplies, water conservation techniques, small and large dams, and, possibly, transbasin diversions in areas of high future potential and need. Here is another challenge: to improve the planning and design of water development projects, like the Sardar Sarovar Project in India, so that environmental impacts of these projects are improved and people adversely affected by the projects are properly compensated (Seckler 1992).

Ten years ago, I published a paper with a title similar to this one (Seckler 1985). After finishing that paper, I considered ending my work on water problems and turning to other research interests because I thought there was not much more of fundamental interest to learn. That paper turned out to be a new beginning, not the end, of my research interests in this field. In the new era of water management, the field of learning is wide open. Indeed, one of our challenges is to unlearn what we thought we knew so well and to start afresh.

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David Seckler

David Seckler is Director General of the International Irrigation Management Institute (IIMI), which has its headquarters in Colombo, Sri Lanka. He is well-known as an international agricultural researcher and scholar.

Dr. Seckler received his initial training in economics from the University of Denver and a PhD from the London School of Economics. He has held teaching and research posts at the University of California, Berkeley and Colorado State University. He also has developed technology for which he holds patents in center pivot irrigation and waste recycling.

Dr. Seckler was Project Officer at the Ford Foundation in India, Senior Policy Adviser at the United States Agency for International Development (USAID), Jakarta, and Director of the Center for Economic Policy Studies at Winrock International in Washington, DC.

He has lived and worked in the United States, England, India, and Indonesia, and has consulting experience in twenty-five countries in Asia, Africa, Europe, and Latin America. He is the author/editor of five books and over fifty journal articles pertaining to the fields of environmental and resource economics, economic development, policy and theory, irrigation economics, social philosophy, and private sector development.

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