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Research Report

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

David Seckler

International Irrigation Management Institute

Research Reports

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Research Report 1

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David Seckler

International Irrigation Management Institute
P O Box 2075, Colombo, Sri Lanka

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Summary

This paper addresses recent developments in the field of water resources that have substantial practical implications for water policies, programs, and projects. But as noted in Keller, Keller, and Seckler 1995, these concepts and their practical implications appear to be difficult for some professionals in the field to grasp—or, at least, to accept. This extended synopsis summarizes the logic of this argument in the hopes that the larger discussion will become clear.

"Efficiency"

Procuring additional fresh water supplies is highly problematical. As a result attention has naturally turned to "demand management" in the hopes that increased efficiency of water use will produce sufficient savings to meet future water requirements. Proponents of demand management point to the successes in the energy sector of developed nations where projections of rising energy demand were largely obviated by increased efficiency of energy use. Thus they contend that physical water use efficiency can be increased by using less water per unit of output. Similarly, economic efficiency can be increased by reallocating water from lower valued to higher valued uses.

Indeed, irrigated agriculture consumes over 80 percent of the world's developed water supplies, and the water use efficiency of a traditional gravity irrigation system is only about 40 percent. But sprinkler irrigation systems are typically around 70 percent efficient and drip irrigation system efficiency can be as high as 90 percent. Thus, it appears that at least one-half of the water currently used in irrigated agriculture could be saved through increased irrigation efficiency. But in the field of water, "efficiency" is a tricky concept. To understand it, we must first understand the basic features of water basins.

Water basins

When a unit of water in a water basin is *diverted* from a *source* to a particular use, three basic things happen to it. First, a part is lost to the atmosphere because of *evaporation* from surface areas, or evapotranspiration from plants, or both. Second, the part of the diverted water that has not evaporated *drains* to surface or subsurface areas. It may drain to the sea, a deep canyon, or a similar *sink* where it cannot be captured and reused, in which case it is truly lost to the system. Otherwise, the drainage water flows back into a stream or to other surface and subsurface areas where it can be captured and reused as an additional source of supply. This water is not lost or wasted in physical terms. Third, drainage water becomes *polluted*. It absorbs, or "picks up," pollutants as it is used, and these pollutants are concentrated by evaporation. Thus, as water cycles and recycles through the system, it eventually becomes so polluted that it is no longer usable and must be discharged to a sink.

If water is plentiful this is not a problem, which is the case when water basins are open. In the open state, usable water flows out of the water basin (which should include estuaries) to a sink, even in the dry season. The only problem involved in meeting new demands in the open state is to capture and distribute this water for beneficial use. But as population and economic activity grow in a water basin, it gradually evolves from an open to a closed state, where all the dry-season flow of usable water is captured and distributed. Most of it evaporates and whatever remains is so polluted that it cannot be used.

This creates massive "head ender-tail ender" problems at the level of the entire water basin. Tail enders—those users at the bottom of the water basin—receive progressively less water of progressively lower quality. The Colorado River basin is one such example. The water entering Mexico is so polluted that a massive desalinization plant has been built in an attempt to satisfy Mexico's riparian rights. And during the dry season even this water vanishes into the sands of Mexico before the Colorado River reaches the sea.

Water use efficiency

The fundamental problem with the concept of water use efficiency based on supply, that is, diversion to a project, is that it considers inefficient both the evaporative loss of water *and* the drainage water. This is invalid for that part of the drainage water which can be reused. To overcome this confusion in the concept of water use efficiency, knowledgeable people now distinguish between "real" water savings and "paper" water savings—or, as they say in California, between "wet" and "dry" water savings—as illustrated in a simple example:

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. Similarly, it is said, water savings of more than 50 percent can be achieved by low-flow toilets and showers.

Let us look at this example more closely. By turning off my faucet, I leave 40 gallons in the source of water for use elsewhere in the water basin system. But what happened to the water that I previously had wasted—before I started turning off the faucet? It went "down the drain." But then where did it go? If the 40 gallons were captured and used by someone else downstream, my wastage was not lost to the system. Turning off my faucet results only in dry water savings; the supply of water in the water basin as a whole has not changed.

The same distinction between wet and dry savings applies in the slightly more complicated case of irrigated agriculture. Assume that a 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 have evaporated, mainly to meet the evapotranspiration requirements of the crop, while the other 500 units of the water are lost by surface and subsurface drainage. But 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 have evaporated while 250 units are lost to drainage. Now the overall irrigation efficiency of the system, of *A* and *B* together, has increased to 750 units of water divided by the 1,000 units of initial water supply, or 75 percent. Overall efficiency increases further if another group of farmers, *C*, used the drainage water from *B*—and so on. Without pollution the water basin as a whole eventually would converge to nearly 100 percent efficiency. For this reason, if all the farmers in the water basin adopted sprinkler irrigation, which has an irrigation efficiency of 70 percent, only the distribution of water, not the total water supply or the irrigated area, would change.

Conclusion

As water basins become closed, they become, by definition, more efficient. This is why the scope for improving water use efficiency is low, and the degree of water scarcity in the future will be greater than commonly assumed. This is the central problem of the new era of water resources management. Careful research and development work is needed to create wet water savings—and to avoid chasing the red herring of dry water savings. The opportunities for creating wet water savings lie in four principal directions:

Increasing output per unit of evaporated water

Reducing losses of usable water to sinks

Reducing water pollution

Reallocating water from lower valued to higher valued uses

While considerable progress can be made in achieving wet water savings, it is clear that some of the most rapidly growing areas of the world also will require additional water development programs. This is another challenge in the new era of water management: to design and implement these projects in a much better way—from all the important technical, economic, social, and environmental perspectives—than they have been in the past.

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

David Seckler[1]

Introduction

A few months ago I met with Ismail Serageldin, vice president of the World Bank and chairman of the Consultative Group on International Agricultural Research (CGIAR). 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 always had thought that water was important, I had not thought that it was *that* important. But considering that the population of virtually every country 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 now am persuaded that 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. In North Africa, 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. And as these words are being written, an official of the Government of Sudan has threatened to disrupt the supply of Nile water to Egypt by unstated means (Washington Post, 15 July 1995, p. A 18). Similarly, the conflict over water rights also is exacerbating tensions between Palestine and Israel.

In yet another dimension of the problem, India's future food security depends crucially on development of additional irrigated area. Indeed, over 70 percent of all of the additional food grain production in Asia since the beginning of the green revolution in the late 1960s has been on irrigated land. But 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 the high-yielding varieties (HYVs) and inorganic fertilizer, and the rapid expansion of irrigated area. Now, however, the gap is closing. The practical yield potential of the HYVs is being reached in most countries due to high rates of fertilizer use, and the net growth of irrigated area in the world is now probably *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

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[1] Director General, International Irrigation Management Institute (IIMI). I am grateful to Henrik von Loesch for major editorial help in writing the summary and to the USAID-Winrock Environmental Policy and Training Project, the Ford Foundation, the International Irrigation Management Institute, and Winrock International for supporting research for this paper. I am also grateful to the following people for helpful comments on the paper: Randolph Barker, Andrew Keller, Jack Keller, Jacob Kijne, Chris Perry, David Purkey, Robert Rangeley, Daniel Renault, and R. Sakthivadivel.

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. 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 government began tracking it in the 1960s" (Wall Street Journal, 11 July 1995, p. A2).

Hence, part of what I mean by "the new era of water management" refers to the increasingly difficult problems facing water management all around the world. But 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 good solutions to problems are the result of defining as precisely as possible what a problem is, as well as what it 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. And once we understand this problem clearly, we can avoid pursuing red herrings, rather focusing our thinking on the kinds of creative and innovative devices that will lead to real solutions of the problem. That is the subject of Part II.

Part I — The Problem of Water Management

Water basins: Sources, sinks, and recycling

To fully understand the generic problem of water management, it is necessary to think in terms of water basins as whole units. There are several well-known facts about water basins 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 water basins (see Keller, Keller, and Seckler 1995).

The sources of water in a basin are: (a) 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; (b) trans-basin diversions from water-surplus to water-scarce basins; and (c) desalinization of seawater.

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

This problem becomes even more acute in the light of the fact that the supply of and demand for water vary dramatically by season. In the wet season the demand is low and the 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 by country, such as those of 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 annual averages.

The water sinks are: (a) water evaporated to the atmosphere from surfaces and the evapotranspiration of plants; (b) surface and subsurface flows of usable water to salt sinks—oceans, inland seas, or saline aquifers;[2] and (c) 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 water basins is that a substantial amount of water is recycled between the sources and the sinks. Because of recycling, it is helpful to think 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:

> Part is *evaporated* and lost to the atmosphere.
>
> The remainder is *drained* from the point of use to some other surface or subsurface place in the system.
>
> Some amount of salt or other pollutants is picked up, or *absorbed,* in the use of the water and carried in the drainage water.
>
> The *concentration* of pollution in the drainage water increases both because of 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 a sea. 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 less water runs off than was initially provided. This consumptive use of water concentrates the pollutants that were in the input water. Thus as water is repeatedly recycled in the water basin, the amount and concentration of pollutants it carries increase substantially.

On the other hand, if the polluted drainage water is blended with less polluted water, the concentration of pollutants in the total water supply decreases, and the water can become more usable even though the amount of pollutants in the two blended streams has not changed. This blending effect is not valid for highly toxic, nondegradable pollutants such as heavy metals. But, for example, saline drainage water from irrigated lands 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 in drinking water.

Open and closed water basins

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

[2] Estuaries could be included as part of the water basin, and estuarian benefits could be counted as a beneficial use of water. But this complication is ignored here.

"closed"—i.e., there is no usable water leaving the water basin.

A closed water basin can be reopened. In terms of annual supplies of water, it can be reopened by trans-basin 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. But these traditional "water development" techniques eventually reach the limits of economic and environmental viability and the water basins become permanently closed for all practical purposes. The Nile water basin, and many other water basins in the Middle East are or soon will be permanently closed. The same is true of major river basins in Asia.

As water basins approach closure, massive "head ender-tail ender" problems develop, with the tail enders at the bottom of the water basin receiving progressively less water of progressively worse 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 tail end of the water basins. This can cause major problems. For example, studies indicate that around Lake Manzalla near the mouth of the Nile villagers' life expectancy is only 38 years because of water pollution.

Local and global water use efficiency in water basins

A well-known facet of the optimization theory is that it is possible to obtain a "local optimum" position in a suboptimal portion of the whole system. This can easily happen in water basins, especially in closed water basins. 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. The implication is clear—through such simple devices enormous quantities of water can 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 case of tooth brushing, the same function (brushing teeth) is achieved with substantially (on the order of 90 percent) less water. This gain in efficiency requires substantially less water to be diverted for toothbrushing and can be used to serve other needs. Or as the number of tooth brushers increases, their needs can be met by the spread of increased efficiency among existing tooth brushers, without increasing the supply of water for this purpose.

But is this position valid at the global level, in terms of higher water efficiency in the water basin as a whole? When water flows out of a faucet, it "goes down the drain." Since drains typically are pipe systems, there is little evaporation of drainage water. The water disappears from view but does not disappear from the system. Because all of the efficiency gains in this toothbrushing example are local efficiency gains due to reducing drainage water, *the gain in 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.[3] But 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 toothbrushing decrease, and water is saved in this dimension, the flow of drainage water back into the water supply decreases by the same amount. Thus, the total water supply in the water basin 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 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 used beneficially to meet the evapotranspiration requirements of the crop, while the other 500 units of the water are lost to these farmers' fields by surface and subsurface drainage. But assume that a second group of farmers, *B*, captures all 500 units of drainage water from *A* and applies it to their fields at 50 percent efficiency. They use 250 units of the drainage water beneficially to meet evapotranspiration requirements, but again, 250 units are lost to drainage. The overall, global irrigation efficiency of the system, that is, of *A* and *B* together, has increased to 750 units of water used beneficially 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 was beneficially used downstream, this would be only a "dry" water saving. But if the drainage water flowed directly into a salt sink, "wet" water would be saved. By definition, all of the usable drainage water in closed water basins is already being beneficially used, and 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. Reducing this loss by reducing drainage water will result in "wet" water savings, a real gain 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 to water resources analysis.

In sum, real global gains in water efficiency achieved by reducing drainage losses depend on whether the water basin is open or closed. But this is only one source of efficiency gain. Whether in closed or open

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[3] Direct drainage to the sea accounts for a large percentage of the real water losses by 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.

water basins, real efficiency gains also 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 thinking about water resources in this new way—that is, in terms of the total water basin—is that conventional estimates of water demand and supply—past, present, and future—become highly ambiguous. Most of the data are based on the amounts diverted to the various sectors, with the sum of all diversions taken as the aggregate demand for water. But this tells us nothing about water demand in relation to primary water supply. Since much of the water diverted is recycled, from previous diversions, it is very difficult to know what supply and demand figures actually mean in such publications as World Resources Institute 1994. Clearly, we need a concept of *net diversions.* We need a portmanteau term that distinguishes between "wet" and "dry" water in our conversation, writing, and most importantly, thinking.

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

Of these three, it is most 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). But if, as in the case of salt pollution in concentrations below the threshold levels of crops, it only reduces the productivity of water, there is no physical, only an economic, measure of the amount of water involved. However, 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 dilute it back down to its original concentration of pollutants. This could be the basis of a pollution tax on water, for example, 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 that must simply be prohibited from entering the water stream. But on the whole, this provides a reasonable, if rough, measure of the 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 provides 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 demand for food and, therefore, for water for irrigated agriculture also will be lower (Seckler 1993, 1994).

Urban and industrial demand for water, however, is largely a function of the rate of economic growth—which is now much higher in developing countries, especially in Asia, than it has been in the past. Large amounts of water already 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 opportunity for real water savings occurs in coastal urban areas where drainage water now is simply dumped into sinks, causing the consumptive use of water to approach 100 percent of the water diverted to these areas.

But 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 1994), which leaves only 8 percent for the other sectors.

Unfortunately, the environmental sector also can be a highly consumptive user of water because of streams that discharge into sinks and large shallow surfaces of water exposed to evaporation in rivers, lakes, and wetlands. 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 critically important sanctuary for migratory birds and other wildlife. But 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 the other sectors generally expressed 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, thus opposing water projects. The political power of the environmental sector assures that developing additional supplies of water through additional projects to meet increasing demands (even environmental demands) will become more difficult in the future. It is rightly said that "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 with a brief review of the basic principles of irrigation.

Evaporation: Eto and Eta

The evaporative use of water in irrigated agriculture is partly due to evaporation from exposed surface areas of water in the irrigation and drainage canal systems and on the surfaces of fields, but it is mainly due to the evaporative requirements (or evapotranspiration) of plants. The rate of evaporation is determined mainly by the "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. But 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*. Table 1 shows the seasonal crop coefficients of some major crops under the *same Eto conditions*.

TABLE 1.
Seasonal Crop Coefficients.

Crop	Condition		Crop	Condition	
	Moist[a]	Dry[b]		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	0.70	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 (μ < 5 m/s).
[b] Low humidity (RH_{min} < 20%) and strong wind (μ > 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 high *Eta* crops with low *Eta* crops. There are two problems with this view. First, as shown in table 1, there is little difference in *Eta* among major crops *under the same Eto conditions*. Second, crop yields and *Eta* are highly correlated: 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).

While it is thus 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 12 to 18 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).[4] Large savings also can be achieved by moving crop production from high *Eto* regions to low *Eto* regions—for example, out of windy regions to more tranquil regions. In addition, it should be noted that most trees are heavy evaporative consumers of water because of the large surface area of their 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 upper Nile around Luxor during the hot, windy season, but were grown lower in the Nile where it is cooler and winds are less severe. 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.

This presents 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 and a nine-month variety of sugarcane, for example, would be very helpful. Also, if possible, it would be valuable to find economical plant species and varieties that have lower *Eta* in hot, windy regimes—like olive. Are there valuable plants that shut down, like cactus, when the heat (and wind) is on?

Water application

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 (especially in the tails of the system), sometimes at a critical growth stage of the crop, causing substantially reduced yields. Part of this problem is due to mismanagement and part to "surge" effects in the supply of water to the farmers' fields. This problem can be solved by standby tube wells 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. But 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. But if these are salt sinks, the drainage water creates waterlogging and salinity problems. Similarly, good quality drainage water is often dumped to

[4] In many of the tropics, however, 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.

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 because in many water basins 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. Since yields in most irrigated areas have increased substantially over the past few decades, evapotranspiration should also have increased. If this is true, then 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 more poorly—e.g., with more tail-ender problems—than they have in the past. They may, in fact, need more water inputs.

Managing water to increase productivity

These considerations deserve serious thought about policy and management issues. One issue is to decrease the variability of the water supply through better conjunctive use of water (with deliberate over-irrigation in times of surplus to recharge aquifers) and pumping into the canal systems, as well as from private tube wells. Another way to increase the 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. But 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 (C. Perry, personal communication, 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 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 in this manner. 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 subsurface moisture and mine high water tables. But if fallow lands are kept barren and a "dust mulch" of loose soil on the surface is maintained, 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. But 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 occurs in the planting season because of high evaporation losses before the crop cover is established. An International Irrigation Management Institute (IIMI) study of dry seeding rice in the Muda Irrigation Project of 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 1995). 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*. Sprinkler irrigation systems, however, are not so efficient. In fact, 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 and 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 and a considerable amount of subsurface water storage. A substantial, although unknown, part of the *Eta* of crops in Egypt is met through subirrigation. Similarly, in Indonesia stream barrages lower drainage losses from rice 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 tube wells, these systems can lower water tables and be used to drive salts below the root zone of plants, where it can be permanently and harmlessly stored. 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, that is salt-loving plants (I am grateful to Jack Keller for this information). 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 is highly salted, is used to irrigate halophytes. Then the drainage water from the halophytes, which may have a higher concentration of salts 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.

Economic considerations

Turning to the economic dimensions of the problem, it is clear that the productivity of water can be increased by substituting crops with high economic value per unit of water consumptively used for crops with low value. While this is valid in principle, it may not be easy in practice. 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 would be idle. But if the net value of a crop is higher than that of another crop in that same 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. Reducing fertilizer use by such means as a tax on fertilizers may then be appropriate.

Last, 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," if you will, 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 areas of high water availability. Carruthers (1993) contends that in the future 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 water basins in the world are encountering water scarcities, then, obviously, the scope of international trade in agricultural commodities requiring large volumes of water 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. But, 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, trans-basin diversions to 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 the negative environmental impacts of these projects are ameliorated 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. But 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.

Literature Cited

Agcaoili, M., and M. W. Rosegrant. 1995. Global and regional food supply, demand, and trade prospects to 2010. In *Population and food in the early twenty-first century: Meeting future food demand of an increasing population,* ed. Nurul Islam. Washington, D.C.: International Food Policy Research Institute.

Bhuiyan, S. I., M. A. Sattar, and M. A. K. Khan. 1995. Improving water use efficiency in rice irrigation through wet-seeding. *Irrigation Science* 16(1): 1–8.

Carruthers, I. 1993. *Going, going, gone! Tropical agriculture as we knew it.* Occasional Paper no. 93/3. London: Wye College, University of London.

Department of Water Resources, State of California. 1994. *California water plan update.* Vol. 1, Bulletin 160–93. CA, USA: Department of Water Resources, State of California.

Frederiksen, H. D., and C. Perry. 1995. *Needs and priorities in water-related research.* Draft paper. Colombo, Sri Lanka: International Irrigation Management Institute.

Hargreaves, G. H., and Z. A. Samani. 1986. *World water for agriculture—precipitation management.* Washington, D.C.: Agency for International Development.

Keller, A., and J. Keller. 1995. *Effective efficiency: A water use efficiency concept for allocating freshwater resources.* Water Resources and Irrigation Division (Discussion Paper 22). Arlington, Virginia, USA: Winrock International.

Keller, A., J. Keller, and D. Seckler. 1995. *Integrated water resource systems: Theory and policy implications.* Colombo, Sri Lanka: International Irrigation Management Institute.

Seckler, D. 1985. The new era of irrigation management in India. *Journal of the Indian Water Resources Society* 29–39) January.

Seckler, D. 1992. *The Sardar Sarovar Project in India: A commentary on the report of the independent review.* Water Resources and Irrigation Division (Discussion Paper 8). Arlington, Virginia, USA: Winrock International.

Seckler, D. 1993. *Designing water resources strategies for the twenty-first century.* Water Resources and Irrigation Division (Discussion Paper 16). Arlington, Virginia, USA: Winrock International.

Seckler, D. 1994. *Trends in world food needs: Toward zero growth in the 21st century.* Water Resources and Irrigation Division (Discussion Paper 18). Arlington, Virginia, USA: Winrock International.

Willardson, L. S., R. G. Allen, and H. D. Frederiksen. 1994. Universal fractions and the eliminations of irrigation efficiencies. Draft paper presented at the 13th Technical Conference, United States Commission on Irrigation and Drainage, Denver, Colorado, 19–22 October 1994.

World Resources Institute. 1994. *World resources 1994–95.* New York: Oxford University Press.

Research Reports

1. *The New Era of Water Resources Management: From "Dry" to "Wet" Water Savings.* David Seckler, 1996.

Forthcoming

2. *Altemative Approaches to Cost Sharing for Water Service to Agriculture in Egypt.* C.J. Perry, 1996.

3. *Integrated Water Resource Systems: Theory and Policy Implications.* Andrew Keller, Jack Keller, and David Seckler, 1996.

4. *Results of Irrigation Management Turnover in Two Irrigation Districts in Colombia.* Douglas L. Vermillion and Carlos Garces-Restrepo.

INTERNATIONAL IRRIGATION MANAGEMENT INSTITUTE
P O Box 2075 Colombo, Sri Lanka
Tel (94-1)867404 Fax (94-1) 866854 E-mail IIMI@cgnet.com
Internet Home Page http:/ /www.cgiar.org