3

Research Report

Integrated Water Resource Systems: Theory and Policy Implications

Andrew Keller, Jack Keller, and David Seckler

International Irrigation Management Institute

Research Reports

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Contents

Summary

Over the past several years we have been developing a concept of integrated water resource systems (IWS) that has substantially changed our own views on this subject. IWS is a "composition" of already familiar parts. The interesting thing about compositions is that they can lead to highly counterintuitive results. For example, we show that attempts to increase irrigation efficiency at the micro level often lead to reduced irrigation efficiency at the macro level.

This particular paper was stimulated by a public debate, which pitted the growing call for demand management against advocates of supply augmentation. Two of the present authors presented the opposition view, largely on grounds of IWS. While we naturally felt we won the debate, it was apparent that even those of the audience who agreed with our conclusions were not entirely clear how we got there. This paper is an attempt to present the concept of IWS as clearly and simply as possible so that our supporters can more readily defend, while our opponents can more sharply criticize, our position.

The paper focuses on the irrigation sector, which is by far the largest and most complex user of water in the world. We show how the *classical* concept of irrigation efficiency can lead to erroneous conclusions and serious mismanagement of scarce water resources. This is because the classical approach ignores the potential reuse of irrigation return flows; in other words, it fails to consider the integrated nature of water resource systems.

We introduce the concept of *effective efficiency*, which, by accounting for the amount of freshwater *effectively* consumed, overcomes the limitations of the classical approach. Freshwater is effectively consumed when it is lost by evapotranspiration, flows to a sink, or is degraded in quality. Reductions in effective consumption result in *real water savings* and higher effective efficiencies.

A water resource system is "closed" when there is no usable water leaving the system. Conversely, a water resource system is "open" when usable water does leave the system. Most of the important policy questions in the water resources field depend on the degree of closure of these systems, and on a thorough understanding of the integrated nature of these systems.

As an IWS begins to close, it becomes increasingly more difficult to save water, and tradeoffs emerge among the different opportunities for water conservation. There are important policy implications for systems that are nearing closure as well:

1. In a closing system all users become increasingly interdependent. Each use cycle reduces the relative supply for someone downstream by reducing the quantity and/or quality of the water that is discharged. Management of the interdependence becomes a public function. Ultimately, a closing system requires much more management than an open system.
2. Strategies to improve and manage efficiency differ from one part of the system to another and at different levels within the system. Such differences must be factored into the analysis, planning, and management of water resources.
3. Water management in closing systems requires increasingly efficient and effective management (conjunctive use) of both surface water and groundwater.
4. Managing closing systems requires flexibility to be able to move water where and when it is needed to maximize the water multiplier and to increase its aggregate value.
5. The key to effective management of water resources in closing systems is the ability to allocate and reallocate water to accommodate changing demands and priorities.

This paper deals with physical efficiency—not with the much broader concepts of economic and environmental efficiency. For example, even if a closed irrigation IWS were operating at nearly 100 percent overall physical efficiency, substantial eco-

nomic gains could be made by reallocating water from lower- to higher-valued uses. Furthermore, both physical and economic efficiencies must be estimated on the basis of true consumptive use and not on diversions, which is why the concepts of integrated water resource systems and effective efficiency are so important.

Integrated Water Resource Systems: Theory and Policy Implications

Andrew Keller, Jack Keller, and David Seckler

Those, who are strongly wedded to what I shall call the classical theory, will fluctuate, I expect, between a belief that I am quite wrong and a belief that I am saying nothing new.

John Maynard Keynes
Preface to *The General Theory of Employment, Interest, and Money*

Introduction

Over the past several years we have been developing a concept of integrated water resource systems (IWS) that has substantially changed our own views on this subject. This concept was first explicitly outlined in the proceedings of the Water Resources Roundtable held in Alexandria, Egypt in April 1992.

The response of many to IWS has been similar to the reactions to Keynes' great work, which he so presciently stated in his preface. We believe that this common response stems from a common cause. Both Keynes' *General Theory* and our, much more modest, efforts in water resource systems are not so much analytical as they are a synthesis of already known facts into an integrated whole. Both, in other words, are "compositions" of already familiar parts. But the interesting thing about compositions is that they can lead to highly counterintuitive results. These are described as "composition phenomena," "emergent properties," or "scale effects."

For example, in his famous "savings paradox," Keynes showed that efforts by individuals to increase savings are likely to lead to a decrease in the total amount of savings in the economy as a whole. Similarly, we show that attempts to increase irrigation efficiency at the micro level often lead to reduced irrigation efficiency at the macro level. These paradoxical and counterintuitive aspects of composition problems make them difficult to understand and use, especially for those well trained in other perspectives and modes of thought. (The economist Paul Samuelson said that there are two kinds of economists in the world: those who were older than 28 years in 1936, when Keynes published the *General Theory*, and those who were younger. The former never did really get it.)

We have found that as the IWS concept has gradually taken root, we have had to dramatically change our thinking about water resource systems and policy. Indeed, some of our previous pronouncements and publications on the subject are rather embarrassing. Similarly, many of the pronouncements and publications of some of our most respected colleagues now seem to be patently mistaken. We have also experi-

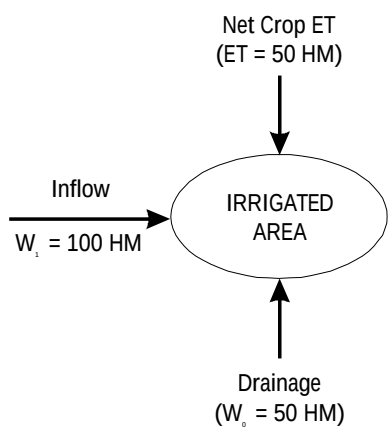
enced considerable frustration in attempting to explain the IWS theory to others and to train them in its use. This is especially true of people who are well trained in the standard paradigm of water resource engineering and economics. Interestingly, however, this is not true of people (rather like Samuelson's less than 28 year-olds) who are not well trained. It appears to them, as it now appears to us, rather obvious and commonsensical.

This particular paper was stimulated by a public debate[1] in December 1994 on water resource policies, that was sponsored by the USAID through its ISPAN Project. The debate pitted the growing call for demand management against advocates of supply augmentation. Two of the present authors presented the opposition view, largely on grounds of IWS. While we naturally felt we won the debate, it was apparent that even those of the audience who agreed with our conclusions were not entirely clear how we got there. This prompted an offer from the USAID-Winrock Environmental Policy and Training (EPAT) Project to write out the concept of IWS as clearly and simply as possible so that our supporters can more readily defend, while our opponents can more sharply criticize, our position. That is what this paper attempts to do.

The Composition of an Idealized IWS

This paper focuses on the irrigation sector, by far the largest and most complex user of water in the world. We begin with an idealized basic irrigation module (see figure 1) that can be replicated to form an irrigation system.

FIGURE 1.
Example of an idealized basic irrigation water flow module in which net crop ET plus drainage equal the inflow.



1. An initial supply of water, or inflow, W_I = 100 hectare-meters (HM), is diverted from a "source," such as a river, reservoir, or aquifer and applied to an irrigated field.
2. Because of evaporation from the soil surface and transpiration of plants, or *crop evapotranspiration* (ET), some of this water, say 50 HM, passes to the atmosphere as a vapor and is lost from the system. This is evaporative depletion.
3. The balance of the water, W_0 = 50 HM, then flows out as surface and subsurface drainage.

Classical irrigation efficiency

In the classical model of irrigation efficiency, drainage water is treated as though it flows to an ultimate "sink." It simply drops out of the system, or "disappears." The part that vaporizes as crop ET is beneficial evaporation. Thus the classical irrigation efficiency, E_C, for the above case is:

$$E_c = \frac{\text{Volume of beneficial evaporation}}{\text{Volume of water diverted}}$$

$$= \frac{\text{Net crop ET}}{\text{Volume of inflow}}$$

$$= \frac{50\ \text{HM}}{100\ \text{HM}} = 50\%$$

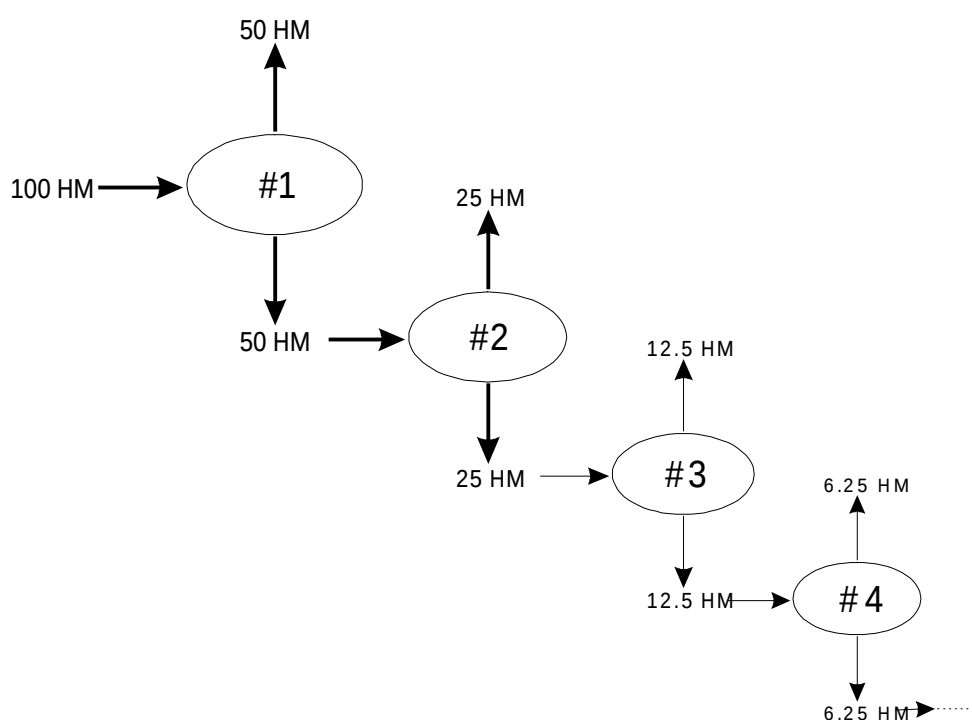
[1] *Water Strategies for the Next Century, Supply Augmentation vs. Demand Management*, a debate sponsored by the U.S. Agency for International Development and the Irrigation Support Project for Asia and the Near East (ISPAN), September 26, 1994, U.S. Department of State, Washington, D.C. Peter Rogers and Kennith Frederiksen presented the demand management, and David Seckler and Jack Keller the supply sides of the debate.

In practically all IWS, however, the drainage water stays in the system and is incorporated into the initial water supply for additional irrigation applications. To illustrate this important fact, a series of irrigation modules[2] for an "idealized" IWS is shown in figure 2. The first module of figure 2 is the same as that in figure 1. The second module receives only the 50 HM of drainage outflow water as its initial supply. Assuming the classical irrigation efficiency, $E_C = 50$ percent, for all the modules, the crop ET in the second cycle consumes 25 HM, leaving 25 HM of drainage. Again, this 25 HM of drainage from the second module flows to a third module and is divided into crop ET and drainage, which flows to a fourth module, and so on.

We are starting with an idealized model in which the water is pure (salt- and pollution-free) and there is no rainfall. Furthermore, the only water "lost" from the system is to the atmosphere, which results from crop ET, there being no other evaporation. In the next section we will discuss the nonidealized, or real, case in which there are salts and pollution in the water supply and non-beneficial evaporation losses from the system.

The IWS of figure 2 represents what we call a "closed" water system. In a perfectly closed system, all of the drainage water from one use cycle (module) returns to the initial system and becomes available for reuse. In such a perfectly closed IWS, the iterative process will continue until the initial water supply is totally consumed by crop ET.

FIGURE 2.
Example of a series of irrigation cycles (like in figure 1) showing the water flow sequence when net crop ET and drainage are both 50 percent of the inflow to each use cycle.



[2]We use the terms "module" and "cycle" interchangeably, but tend to use "module" when referring to individual areas and "cycle" when referring to processes or a series of modules.

Table 1a shows the amounts of water supplied or diverted, net crop ET, the classical efficiency for each use cycle in figure 2, and their totals. By the end of the fourth cycle, only 6.3 HM of water are left, and by the end of the tenth cycle, essentially all the water has been consumed by crop ET. Furthermore, it is interesting to see that the sum of water diversions for the 10 use cycles, 199.8 HM, is twice as much as the initial 100 HM freshwater supply available to the system.

TABLE 1a.
The consumption by crop ET of a 100-HM freshwater supply as it passes through 10 irrigation use cycles, each with an E_C = 50% and an E_E = 100%, (as depicted in figure 2).

Use cycle	Water diverted to the cycle (HM)	Net crop ET within the cycle (HM)	Classical efficiency for the cycle, E_C, (%)	Effective efficiency, E_E (%)
1	100.0	50.0	50	100
2	50.0	25.0	50	100
3	25.0	12.5	50	100
4	12.5	6.3	50	100
•				
10	0.2	0.1	50	100
Total	199.8	99.9	50	100

If the diversions to all the uses of water in a closed system are added, *the total water supply of the system will be greater than the initial volume of freshwater supplied to the system*. We call this the "water multiplier" effect (which was directly inspired by the Keynesian income multiplier). In principle, if the classical irrigation efficiency, E_C, is a constant for all users, say 50 percent as in the above example, then in an idealized IWS that is perfectly closed, the water multiplier is $1/E_C = 1/(0.5) = 2$. For the above example, the sum of the diversions thus approaches 200 HM.

Because of the water multiplier, every use of water in a system can be inefficient in the classical sense (in this case only 50% efficient), but the system as a whole can be highly efficient—indeed, in the idealized IWS case, 100 percent efficient. We have included table 1b to demonstrate this. It shows the cumulative net crop ET values (for the data presented in table 1a) and the respective values for classical irrigation efficiency, E_C, of the IWS from its beginning to the end of each use cycle. The policy implications of this emergent property of IWS are, of course, enormous.

TABLE 1b.
The cumulative net crop ET values (from table 1a) and the associated E_C and E_E values for the cumulative area of the IWS from its beginning to the end of each use cycle.

Use cycle	Initial freshwater supply (HM)	Cumulative net crop ET (HM)	Cumulative area classical efficiency, E_C (%)	Cumulative area effective efficiency, E_E (%)
1	100.0	50.0	50	100
2	100.0	75.0	75	100
3	100.0	87.5	88	100
4	100.0	93.8	94	100
•				
10	100.0	99.9	100	100

Obviously, from a resource management standpoint, using the classical concept of irrigation efficiency as the basis for determining IWS allocations can lead to faulty policy decisions. Table 1b shows that in the classical sense, the efficiency of the system depends on the amount of reuse involved within the region or reach being considered. The larger the region or longer the reach, the greater the opportunity for reuse and thus, higher the efficiency. By the end of the second cycle, for example, (50 + 25) HM of the initial 100 HM of freshwater supply to the IWS have been consumed by crop ET, and the global E_C is 75 percent. The efficiency increases as we go from the micro- to the macro (or global) view.

To overcome the inconsistencies associated with classical efficiencies, the concept of effective efficiency was developed by Keller and Keller (1995) for use in water resource planning and for making IWS policy recommendations.

Effective irrigation efficiency

The effective irrigation efficiency, E_E, is the beneficially used water divided by the amount of freshwater consumed during the process of conveying and applying the water. For the first cycle in our idealized IWS case depicted in figure 2, it is computed as:

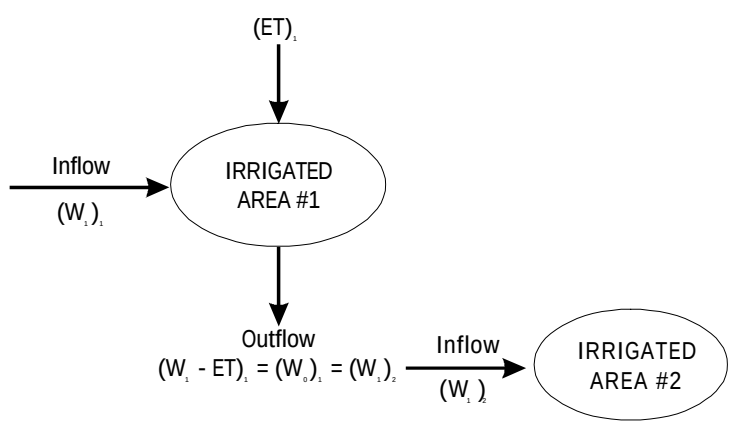
$$E_E = \frac{\text{Volume of beneficial evaporation}}{\text{Volume of water diverted}}$$

$$= \frac{\text{Net crop ET}}{\text{Volume of (inflow - outflow)}}$$

$$= \frac{50 \text{ HM}}{(100 - 50) \text{ HM}} = 100\%$$

Figure 3 shows the generic model of the idealized IWS case in which the inflow water (W_I) is pure, there is no rainfall, and the only evaporation is beneficial crop ET. Furthermore, the outflow $(W_0)_1$ from the first irrigated area, or use cycle, returns to become the inflow $(W_I)_2$ to the second use cycle.

FIGURE 3.
Model configuration for an idealized set of basic irrigation flow modules (like in figure 1) where the drainage from Irrigated Area #1 is the inflow for Irrigated Area #2.



The Composition of a Real IWS

The idealized IWS case discussed up to this point explicitly ignored salts (and pollutants), evaporation other than crop ET, rainfall, and sinks in the system. But every real IWS must have salts,[3] evaporative depletions[4] other than crop ET, and at least one sink.

Sinks are defined here simply as destinations for water that does not enter another module (or get reused). There are different kinds of sinks in a water system but the most certain, and typically the most important, are salt sinks. The initial supply of water to the system contains salts and, likely, other pollutants. As the water cycles through the modules and is depleted by evaporation and crop ET, these salts and pollutants are concentrated in the drainage water. Also, of course, as the subsurface drainage water percolates through the soil, there is potential for considerable "pick-up" of salts and other pollutants. Eventually, the concentration of salts and other pollutants becomes so high that the drainage water is unusable for irrigation purposes and is allocated to a sink, such as the sea or saline lakes and flats. (Note that it is not the quantity of salt but the concentration of salt in the water supply that determines the suitability of the water for irrigation.)

Figure 4 is similar to figure 3, but it shows the generic model for a real IWS. The initial water supply (W_I) of a real IWS contains salts (S_I), has some non-beneficial evaporation (E_{N-B}) in addition to crop ET, and has the potential for some losses to sinks. The parallel arrows are used to represent the dual flows of both W and S and the dual evaporative depletions by E_{N-B} and crop ET.

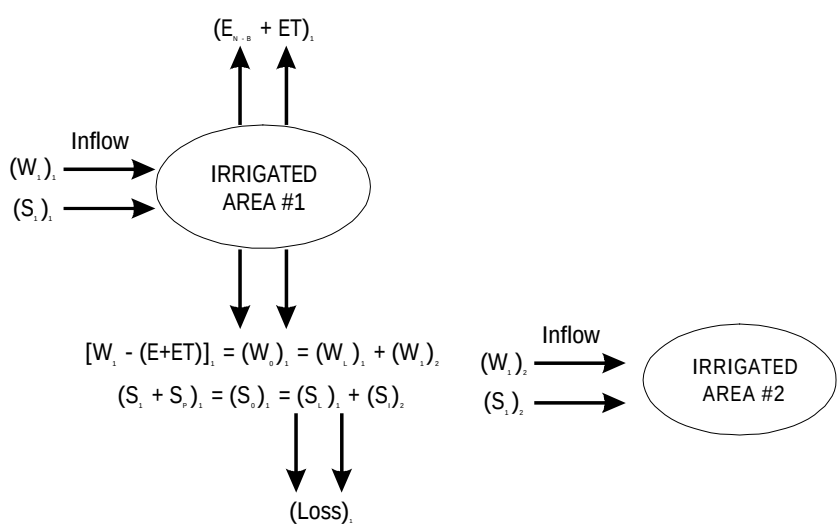
Leaching requirements

For an actual IWS, in addition to the estimated net crop ET, some water should be applied for leaching purposes to maintain a favorable soil salinity level for crop production. The volume of leaching water required to maintain optimum crop production is a function of the specific crop mix and the water quality. The portion of the diverted water that is required for leaching

[3]All irrigation water contains a mixture of naturally occurring salts. The irrigated soil, consequentially, contains a similar mix but at a higher concentration because the salts remain as the water is consumed by crop ET. The extent to which the salts accumulate depends on the irrigation water quality, management practices, and adequacy of drainage. Crop yields will be reduced if the soil salinity becomes excessive. To prevent this, additional water must be applied periodically to leach the accumulated salts from the crop root zone.

[4]Other evaporative depletions include evaporation from open water surfaces such as reservoirs, canals, and drains and the ET from all vegetation except crops. These depletions are usually considered to be non-beneficial.

FIGURE 4.
Model configuration for a set of basic irrigation water flow modules (like in figure 3) with the addition of parallel salt flows and unrecoverable losses.



is called the leaching requirement. Providing the "required" leaching water is equivalent to reducing the volume of inflow available for depletion by crop ET.

The cropping system's leaching requirement (LR) is typically presented as a ratio that can be used to indicate the portion of the diverted water that must percolate below the crop root zone for leaching purposes. The remaining, or "effective", diversion available for depletion by crop ET is (1 – LR) times the actual volume of water diverted. Thus, to accommodate the leaching requirements of an actual IWS, the classical irrigation efficiency becomes:

The LR values are dependent on the irrigation water quality and the percentage of optimum that is acceptable. Fortunately, the leaching requirements for most of the important field, forage, fruit, and vegetable crops have been well researched and documented. These LR values are presented in Ayers and Wescot 1985.

$$E_c = \frac{\text{(Net crop ET) + (Required leaching water)}}{\text{Volume of water diverted}}$$

$$= \frac{\text{Net crop ET}}{\text{(1 - LR) (Volume of water diverted)}}$$

To compute the effective irrigation efficiency for an IWS, the LR of both the inflow water and the outflow water must be considered. This is necessary because the outflow from one cycle becomes the inflow to the next cycle as depicted in figure 4. The equivalent volume of freshwater depletion[5] is the difference between the effective inflow and effective outflow. Thus:

$$E_e = \frac{\text{Net crop ET}}{\text{(Effective inflow) - (Effective outflow)}}$$

$$= \frac{\text{Net crop ET}}{(1 - LR_i)\ \text{Inflow} - (1 - LR_o)\ \text{Outflow}}$$

Computing E_C and E_E values for an actual IWS

Figure 5 shows the water and salt flows through a series of irrigation cycles (see figure 4) beginning with a water supply[6] of 100 HM containing 100 metric tons (T) of salt. The total loss of water to the atmosphere or evaporative depletion during each use cycle is 50 percent of its inflow volume, of which 5 percent is non-beneficial evaporation (E_{N-B}), and the remaining 45 percent is the net crop ET. Thus the drainage from each cycle is also 50 percent of its inflow.

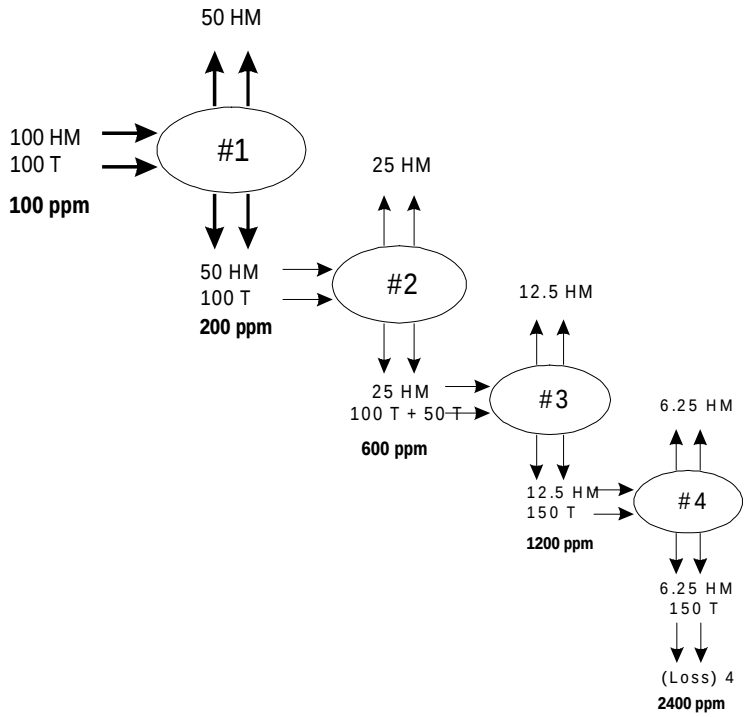
The beginning salinity level of the irrigation water is 100 parts per million (ppm). Since only water, not salt, is lost to the atmosphere, the salt load of 100 T remains in the drainage (or outflow water) from the first use cycle so that the salinity level doubles to 200 ppm. In our example, we show an additional 50 T of salt pick-up or loading as the flows pass through cycle #2. As a result of this salt loading and the evaporative depletion that reduces the outflow to half of the inflow volume, the salinity level jumps to 600 ppm. In cycle #3, it doubles to 1,200 ppm and then doubles again to 2,400 ppm in cycle #4 as the flow continues to decrease by 50 percent as it passes through each use cycle in our example (see figure 5).

By the end of cycle #4, the total evaporative depletion (E_{N-B} and crop ET) for our model IWS is 93.75 HM, and only 6.25 HM of the initial water supply remain. Thus the salt concentration of the initial water supply would have been increased by a factor of 100/6.25 = 16 to 1,600 ppm, even without the additional 50 T of salt picked up during cycle #2. However, as shown in figure 5, this added salt increases the salinity of the residual flow of water to 2,400 ppm, which is quite high. We assumed that no user wanted this water, so we relegated it to a sink allowing the water multiplier to end. It can be concluded from this that the

[5]We considered evaporative depletion by E_{N-B} and crop ET earlier. Here we refer to depletion in terms of the effective loss of freshwater as the result of salinization. For example, if the inflow, LR_I , is 0.1 and the outflow, LR_O, is 0.2, the equivalent freshwater depletion for the module would be 10 percent even if there was no depletion by evaporation.

[6]This still represents a simplified case since in reality diversions rarely equal the total supply of the source. In a real case, there would be a river or other source, with some flow past the points of diversion.

FIGURE 5.
Example of a series of irrigation cycles (like in figure 4) showing the water and salt flow sequence when (net crop ET + non-beneficial evaporation) and drainage are both 50 percent of the inflow to each use cycle.



total water supply in a system is highly regulated by the water quality aspects of the system.

Table 2a shows the values associated with our example for the IWS presented in figure 5. It is similar in form to table 1a for our idealized IWS, but besides the addition of a column for the effective initial freshwater diversions, the multiplier effect stops after cycle #4 because its outflow is lost to a sink. The relative differences between the actual and effective volumes of water diverted for each cycle increase from cycle #1 to cycle #4 because the salt concentration of the inflow water, and consequently its LR values, are increasing.

TABLE 2a.
The E_C and E_E values associated with each of the irrigation use cycles (depicted in figure 5).

	Water diverted to cycle				
Use cycle	Actual (HM)	Effective (HM)	Net crop ET within the cycle (HM)	Classical efficiency, E_C, for the cycle (%)	Effective efficiency, E_E, for the cycle (%)
1	100.0	98.8	45.0	46	90
2	50.0	48.8	22.5	46	88
3	25.0	23.1	11.3	49	89
4	12.5	10.4	5.6	54	54
Total	187.5	181.1	84.4	47	85

It is interesting to note that in table 2a the classical efficiency increased between cycles #2 and #3, and increased even more between cycles #3 and #4. This is an artifact of the design of our example. The increases result from the fact that the net crop ET was kept at 45 percent of the actual diversions, while the effective diversions were decreasing because of the increasing salinity.

What is most interesting about the data in table 2a is that the effective efficiency remains practically constant for use cycles #1, #2 and #3. However, the E_E of cycle #4 drops to 54 percent, which is the same as the E_C. This is the result of loosing the outflow from cycle #4 to a sink. Thus the "effective outflow" (term in the E_E equation) is zero so that E_E and E_C are the same.

Table 2b is based on the data presented in table 2a. It is also similar in form to table 1b for the case of the idealized IWS. Table 2b shows that the difference between the actual and effective initial freshwater supply is quite small. The main reason why the classical efficiencies for the cumulative areas are less in table 2b than in table 1b is because crop ET (E_{N-B} = 0) was the only evaporative depletion for the idealized IWS. Furthermore, since the multiplier effect stops after cycle #4 because its outflow is lost to a sink, the global efficiency only reaches 85 percent.

TABLE 2b.
The cumulative net crop ET values (from table 2a) and the associated E_C and E_E values for the cumulative area of the IWS from its beginning to the end of each use cycle.

	Initial freshwater supply				
Use cycle	Actual (HM)	Effective (HM)	Cumulative net crop ET (HM)	Cumulative area classical effeciency, E_C (%)	Cumulative area effective efficiency, E_E (%)
1	100.0	98.8	45.0	46	90
2	100.0	98.8	67.5	68	89
3	100.0	98.8	78.8	80	89
4	100.0	98.8	84.4	85	85

Real Water Savings

Early attempts in the western United States to stretch water supplies by increasing irrigation application and conveyance efficiencies were unsuccessful and led to the coining of the term "paper water." The term stems from the fact that the classical irrigation efficiency equations used in paper calculations appeared to result in water savings. But in fact, when farmers improved their application efficiency and extended the area irrigated using the apparent water savings, they increased their depletion at the expense of return flows relied upon by downstream users. In many cases, the total area irrigated from the available supply remained about the same. Upstream users expanded their irrigated area while users downstream suffered. In other words, there was no real water saving.

As a result of these experiences, state engineers (who are responsible for water rights allocations in their respective states) now refer to water rights in terms of allowed depletion instead of allowable diversion. Because of this line of reasoning, extensive efforts are made, especially where major water transfers are involved, to separate real water savings, or "wet water," from "paper water," or "dry water."

From an inspection of figure 2 and table 1a for our idealized IWS, it can be seen that for each use cycle E_C is 50 percent and the average systemwide E_C is also 50 percent. But table 1b shows that the global E_C is 100 percent. Thus, improving the effective efficiency of any one use cycle can only produce paper water savings, not real water savings. An inspection of figure 5 and table 2a for our IWS shows that, except for use cycle #4, the effective efficiency is already about 90 percent. The only place where there is significant opportunity for real water savings thus is in cycle #4 where the E_E is 54 percent.

A careful study of figure 5 and tables 2a and 2b reveals that real water savings from our IWS can be obtained by any or all of the following water conservation opportunities (WCOs):

1. Reduce the amount of salt picked up in use cycle #2.
2. Improve the E_C, which is the same as the E_E of cycle #4, and increase its irrigated area proportionally.
3. Reuse the outflow from cycle #4 by employing a fifth cycle before loosing it to the sink.
4. Reduce non-beneficial evaporation (E_{N-B}).

Managing the closure

As an IWS begins to close, it becomes increasingly more difficult to conserve water, and tradeoffs emerge among the different WCOs. We call the selection and implementation of WCOs on a closing IWS, "managing the closure."

Eliminating the salt loading in cycle #2 (the first opportunity in the above list) has the potential of conserving about 1.3 percent of the freshwater inflow. The next two opportunities, taken either separately or together,[7] have the potential of conserving 45 percent of the outflow losses from cycle #4, or about 2.8 percent of the initial supply. Cutting the E_{N-B} losses by 25 percent would reduce them from 9.4 percent to 7.1 percent and conserve 2.3 percent of the initial freshwater supply. However, this would probably be a very expensive undertaking since it would require a conservation program across the entire IWS. Taking full advantage of all four of these WCOs would result in a total conservation savings of roughly 6.4 percent of the initial supply and increasing the global E_E to about 91 percent.

It should not be surprising that the second and third WCOs in the above list provide the greatest savings potential. This is apparent from the fact that E_E is 54 percent for cycle #4; it could potentially be increased to roughly 85 percent by providing a 5th use cycle and minimizing the losses to the sink.

Who is responsible for conserving freshwater?

The question arises as to who should be responsible for water conservation: system managers or farmers. The answer of course is that it takes team work to achieve high efficiency irrigation. Main system managers should be responsible for providing reliable and timely water supplies to farmers while minimizing evaporative depletions and losses to sinks from canal seepage and operational spills. The farmers' responsibility is to use the resources efficiently in those areas of the system where excess seepage and spills from their field operations would be lost to sinks. Since it is costly to achieve high classical irrigation efficiencies, we want to emphasize that increasing the E_C will only produce real water savings where the effective efficiency (E_E) is low, as we have demonstrated for use cycle #4 in our IWS example.

[7]The second WCO has an advantage over the third in that the water quality is higher (1,200 ppm versus 2,400 ppm, see figure 5). This allows more flexibility in the cropping pattern and higher yield potential for an expanded area within the fourth module as opposed to that for an added fifth module. In either case, both WCOs depend on the availability of additional land for irrigation.

Policy Implications of IWS Closure

In sum, a water resource system is "closed" when there is no usable water leaving the system. Either all of the initial water supply has been lost to non-beneficial evaporation and crop ET, or it has such high concentrations of salt and other pollutants that it is unusable. Conversely, a water resource system is "open" when usable water does leave the system. Most of the important policy questions in the water resources field depend on the degree of closure of these systems, and on a thorough understanding of the concepts and differences between efficiencies in the classical and effective sense.

There are important policy implications for systems that are nearing closure, the situation facing most river and groundwater basins in the world's arid regions. *First*, in a closing system all users obviously become increasingly interdependent. Each use cycle reduces the relative supply for someone downstream by reducing the quantity and/or quality of the water that is discharged. Management of the interdependence becomes a public function. Ultimately, a closing water system requires much more management than an open system. If adequate data are available about the nature and source of both surface water and groundwater resources and the dynamics of the system, it is possible to establish realistic and reliable parameters for analyzing and projecting supply and demand patterns.

A difficult part of managing a closing system is developing mechanisms to entice all users to acknowledge their interdependence and to engage them in a negotiation process that binds them to the agreements reached. Without some mechanism to allocate water reasonably among competing interests and to set, monitor, and enforce discharge standards, downstream users are increasingly put at risk. It is usually difficult to develop institutional mechanisms to manage water systems fully, as system boundaries rarely coincide with other administrative boundaries, and the range of authority required for effective system management is seldom vested on a single administrative unit. The difficulty also can be compounded if competing interests are entrenched and powerful, or the river basin is shared by two or more countries or among political jurisdictions.

Thus, efficiency of water use in closing systems increasingly becomes a public rather than a private issue as users must become accountable to each other for the efficiency of use and the quality of discharges. Population growth and increased and diversified demand continually put stress on water supplies. The efficiency of use and/or misuse affects the amount of water needed for any purpose, and thus affects the amount available for competing or for downstream uses.

Second, if we take efficiency to mean the most productive output per unit of water, whether for agricultural production or habitat maintenance, then we can see that strategies to improve and manage efficiency differ from one part of the system to another and at different levels within the system. Such differences must be factored into the analysis, planning, and management of water resources. For example, the drainage water and groundwater in much of northern Egypt's Nile Delta have salinity levels above 3,000 ppm. Thus, excess water applied in irrigation is lost to deep percolation but becomes saline drainage water that, in turn, becomes saline groundwater. From a system perspective, this drainage water is of limited value for reuse by irrigation and industry. Increasing the effective efficiency of this system requires reducing percolation losses and drainage. In contrast, along most of Egypt's Nile Valley and in much of the rest of the Nile Delta, deep percolation either returns to the river or re-

charges aquifers of good quality water that can be tapped as needed. In this case, basin-wide system efficiency objectives can be met even where local irrigation efficiencies are low. In fact, it may even be beneficial to overwater crops or have high seepage losses from the distribution canals to recharge the aquifers.

Along the northern rim of the Nile Delta, excess water acquires a negative value because of its degraded quality. However, along Egypt's Nile Valley and the rest of the Delta, excess water is stored underground, thus increasing its value by making it available for reuse downstream and in other seasons. These examples illustrate how the amount of water that is lost to deep percolation at one point in the system, but which reenters the system downstream as usable return flow, is an important determinant for assessing irrigation efficiency. This is captured in the effective efficiency concepts presented here.

Third, water management in closing systems requires increasingly efficient and effective management (conjunctive use) of both surface water and groundwater. This may include transporting and storing surface water and groundwater in different quantities and qualities, mixing and blending water to improve quality, establishing groundwater recharge programs, regulating groundwater extraction, and perhaps alternating surface application and pumping on a seasonal basis. Such programs present both technical and policy challenges and may require institutional realignments to be successful.

Fourth, managing closing water systems requires flexibility to be able to move water where and when it is needed to maximize the water multiplier and to increase its aggregate value. This "plumbing" issue, closely related to policy issues, is dependent upon the existence of adequate and appropriate institutional mechanisms and the necessary physical infrastructure.

Fifth, water demands change over time, reflecting changes in population and economic structure as well as the changing values of the population. Changes in demand can easily put new stress on water systems as the quantity, quality and location of water use change. Consequently, the key to effective management of water resources in closing water systems is the ability to allocate and reallocate water to accommodate changing demands and priorities. Whether the reallocation function is centralized or decentralized, it needs to be responsive and fluid, able to challenge and modify existing water rights and established water use traditions. The principal opportunities and problems in arid regions with regard to water are virtually defined by two factors: the reallocation of water among beneficial uses to achieve the highest overall benefit in a closing system, and increasing the efficiency per unit of freshwater effectively used for any purpose, especially agriculture.

Finally, we have only dealt with physical efficiency—not with the much broader concepts of economic and environmental efficiency. For example, even if a closed irrigation IWS were operating at nearly a 100 percent overall physical efficiency, substantial economic gains could be made by reallocating water from lower- to higher-valued uses. Furthermore, both physical and economic efficiency must be estimated on the basis of true consumptive use and not on diversions, which is why understanding our concept of effective efficiency and understanding how it differs from the classical concept are so important.

Some readers will claim that the IWS concepts presented here are already well known, and they will ask, "what is new?" We will answer with the question, "if these concepts are so well known, why are we working so hard to increase classical efficiencies at such great cost?"

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