

Discussion Paper

22

**Effective Efficiency: A Water Use
Efficiency Concept for Allocating
Freshwater Resources**

Andrew A. Keller and Jack Keller

**Center for
Economic Policy
Studies**

**Winrock
International
1995**

Center for Economic Policy Studies

The Discussion Paper series is part of Winrock International's effort to develop innovative thinking and disseminate new information about agricultural and rural development. The papers are intended to contribute to the body of knowledge on how development process works, encourage productive debate of development issues, provide a forum for informed opinion, and generate new focal points for research.

The papers represent only the opinion of the authors and not necessarily that of Winrock or any affiliated institution.

Winrock International for Agricultural Development is a private, nonprofit organization whose mission is to reduce poverty and hunger through agricultural and rural development that is sustainable and environmentally sound.

Center for Economic Policy Studies, Winrock International, 1611 North Kent St., Arlington VA 22209, USA

Publications of the Center for Economic Policy Studies

Discussion Paper Series

1. *Economic Regimes, Strategic Investments, and Entrepreneurial Decisions: Notes Toward a Theory of Economic Development*. David Seckler. 1990. 50 p.
2. *Water Policy Innovations in California: Water Resource Management in a Closing Water System*. Jack Keller; N. S. Peabody, III; David Seckler; and Dennis Wichelns. 1990. 49 p.
3. *Environmental and Natural Resource Policy Issues in Developing Countries*. David Seckler. 1992. 24 p.
4. *Irrigation Policy, Management and Monitoring in Developing Countries*. David Seckler. 1992. 31 p.
5. *Agricultural Potential of Mid-Africa: A Technological Assessment*. David Seckler, Doug Gollin and Pierre Antoine. 1992. 164 p.
6. *Implications of Improving Agricultural Water Use Efficiency on Egypt's Water and Salinity Balances*. Jack Keller. 1992. 16 p.
7. *On Institutional Arrangements for Coordinating Large Canal Irrigation Systems with Special Reference to Water Allocation and Cost Recovery in Egypt*. Robert A. Young. 1992. 42 p.
8. *The Sardar Sarovar Project in India: A Commentary on the Report of the Independent Review*. David Seckler. 1992. 13 p.
9. *Successful Small-Scale Irrigation in the Sahel*. Ellen P. Brown and Robert Nooter. World Bank Technical Paper Series No. 171. 1991. 65 p.
10. *The I/E Model: Engineering and Economic Performance Analysis of Pump Irrigation Systems, Version 2.1-A User's Guide. With an Annex: An Evaluation of the Performance of Windpower Water Pumping*. David R. Purkey and David Seckler. 1992. 43 p.
11. *Private Sector Irrigation in Africa*. David Seckler. 1992. 21 p.
12. *Privatizing Irrigation Systems*. David Seckler. 1993. 13 p.
13. *Fertilizers to Support Agricultural Development in Sub-Saharan Africa: What is Needed and Why*. Bruce A. Larson. 1993. 20 p.
14. *"Twenty-five Years of Economic Development" Revisited*. Michael T. Rock. 1993. 38 p.
15. *Population and Environmental Deterioration: A 20-year Retrospective*. Peter Rogers. 1993. 32 p.
16. *Designing Water Resource Strategies for the Twenty-First Century*. David Seckler. 1993. 42 p.
17. *World Grain Consumption and Production: 1961-2030*. David Seckler. 1993. 33 p.
18. *Trends In World Food Needs: Toward Zero Growth in the 21st Century*. David Seckler. 1994. 16 p.
19. *Fertility Rates and Population Projections: Why the United Nations Low Population Projection is Best*. David Seckler and Gerald Cox. 1994. 28 p. (Replaced by Discussion Paper 21)
20. *Transitional Democracies and the Shift To Export-Led Industrialization: Lessons From Thailand*. Michael T. Rock. 1994. 35 p.
21. *Population Projections by the United Nations and the World Bank: Zero Growth in 40 Years*. David Seckler and Gerald Cox. 1994. 20 p.
22. *Effective Efficiency: A Water Use Efficiency Concept for Allocating Freshwater Resources*. Andrew A. Keller and Jack Keller. 1995. 20 p.

Other Publications (Written by CEPS staff or issued under CEPS auspices.

Limited availability)

African Development: Lessons from Asia. Seminar on Strategies for the Future of Africa. 1991. 260 p.

Agricultural Transformation in Africa. David Seckler (ed.) 1993. 208 p.

Assisting Sustainable Food Production: Apathy or Action? Robert L. Paarlberg and Steven A. Breth (eds.) 1994. 92 p.

Issues In African Rural Development 1991. Cheryl R. Doss and Carol Olson (eds.) 1991. 534 p.

Issues in African Rural Development 2. Steven A. Breth (ed.) 1994. 215 p.

Roundtable on Egyptian Water Policy. Mahmoud Abu-Zeid and David Seckler (eds.).1992. 200 p.

Sustainable Agriculture and Economic Development In Nigeria: Lessons from Past Research, Policy Planning and Plan Implementation. Anthony E. Ikpi and Joseph K. Olayemi (eds.) (Forthcoming), 134 p.

Thai Industrial Policy: How Irrelevant Was It to Export Success? Michael T. Rock. *Journal of International Development* (Forthcoming)

Water and Development In Bangladesh: A Retrospective on the Flood Action Plan 1994. 70 p. Peter Rogers, Peter Lydon, David Seckler, and G.T. Keith Pitman. Published by the USAID Irrigation Support Project for Asia and the Near East.

Water Scarcity in Developing Countries: Reconciling Development and Environmental Protection. 1993. 80 p. Deborah Moore and David Seckler (eds.).

Water Strategies for the Next Century: Supply Augmentation vs. Demand Management. 1994. 32 p. Published by the USAID Irrigation Support Project for Asia and the Near East.

SUMMARY

Effective Efficiency: A Water Use Efficiency Concept for Allocating Freshwater Resources

Andrew A. Keller and Jack Keller

Classical water use efficiency concepts are appropriate tools for irrigation design and irrigation management, but they are poorly suited for formulating water allocation and transfer policies. Classical efficiency can be expressed as $E_i = U_{ci} / (1 - LR)V_D$, where U_{ci} is the irrigation water consumed (evaporated) by crops, LR is the leaching requirement (to control soil salinity), and V_D is the irrigation water delivered from a surface or groundwater source to the canals or farm headgates.

Classical efficiency concepts ignore the value of return flows—irrigation water runoff and seepage that re-enters the water supply. Consequently, decisions intended to raise water use efficiency that have been based on classical efficiency calculations often do not result in real water savings. However, many planners mistakenly justify and authorize irrigation improvement projects that are designed to raise a system’s classical irrigation efficiency, E_i , expecting that this will generate real water savings. The savings exist mostly on paper, and the mistake is compounded when “paper” water savings become the basis for expanding the area irrigated or authorizing water transfers (for example to urban users).

To overcome the limitations of classical water use efficiency, we have proposed a new concept, “effective efficiency” (E_e), for water resource decision making:

$$E_e = U_{ci} / U_e$$

where U_e is effective use of water, or the effective inflow less the effective outflow. (In this paper, although we focus on irrigation efficiencies, the effective efficiency concept can be applied to other uses of water and other measures of change in water quality or value.) The effective irrigation efficiency, E_e , takes into account both the quantity and quality of the water delivered from and returned to a basin’s water supply when estimating the total freshwater input for each use-cycle.

We compared classical and effective irrigation efficiencies to demonstrate their differences and the advantage of using E_e for freshwater resource planning and allocation decisions. We did this by computing E_i and E_e for the Grand Valley in the Upper Basin of the Colorado River and the Imperial Irrigation District supplied from the Lower Basin. These are irrigated areas where water conservation projects have resulted in real water savings.

In the Grand Valley, the conservation objective was to reduce the salt loading of return flows that contribute substantially to the Colorado River’s salinity and thus reduce the effective supply to downstream users. The salt loading results when seepage and deep percolation water from the Grand Valley irrigation system (GVIS) flows through the saline strata underlying the valley before returning to the river. The pre- and post-project E_i values are 26.0% and 30.4%, respectively, and the E_e values are 36.8% and 61.7%, respectively.

The small change in the pre- and post-project E_i values results from having reduced the irrigation diversions by only 15% through decreases in seepage and deep percolation. However,

this significantly reduced the salt loading in the Colorado River that results when the irrigation return flows from the GVIS pick up salt as they pass through the saline strata on their way back to the river. Consequently this raised the system's effective efficiency significantly by reducing the effective use from 8.7% to 5.2% of the river's flow at the head end of the valley. Therefore, for the Colorado River's water resources, the conservation program is highly effective. It has resulted in average real water savings of about 3.5% ($8.7\% - 5.2\%$) of the 486,000 hectare-meters used annually or 17,000 hectare-meters per year.

In the Imperial Irrigation District (IID), which is near the terminus of the Lower Colorado River Basin, the objective of current interventions is to effect real water savings through a set of conservation projects that reduce seepage, deep percolation, and operational spill losses. The IID service area overlays a salt sink and drains directly into a salt sink so the irrigation return flows become too salty for agricultural reuse.

Unlike the Grand Valley, which is at a multi-cycle location in the Colorado River basin, the Imperial Valley is at a uni-cycle location. Since the "classical" water losses that become the return flows can not be reused for irrigation, $E_e = E_i$. The set of conservation projects that are being implemented throughout IID's irrigation service area are expected to produce 13,100 hectare-meters of real water savings per year. This will require increasing the average annual E_e from 71.9% to 74.6%.

Egypt's Nile Valley irrigation system (NVIS) is an excellent example of a multiple use-cycle system with a high global efficiency but low local efficiencies. Egypt is interested in expanding the area irrigated by Nile River waters without reducing the high productivity of the present irrigated areas. To accomplish this will require an aggressive conservation program. However, directing conservation efforts toward areas where multiple use-cycles are possible, and thus E_e is already quite high, will result in little real water savings.

Our estimate for the classical irrigation efficiency for the NVIS is $E_i = 41.2\%$. Thus there might appear to be considerable opportunity for conserving water by reducing water losses in the NVIS. Actually, however, the potential water savings are small because the effective irrigation efficiency for the NVIS (based on the cropland U_{ci} and effective use, U_e , values) is $E_e = 91.3\%$, which is already quite high. In fact to achieve real water savings, either the cropland losses to evaporation, U_{ci} , or the losses to phreatophytes must be reduced, and both would be costly.

Although E_i is a useful parameter for irrigation system design and management, we believe E_i values can be dangerously misleading when they are used as indicators for identifying potential water conservation opportunities or quantifying real water savings associated with freshwater conservation programs. E_e , a new irrigation efficiency parameter, quantifies the beneficial irrigation outputs in terms of the effective quantity of water consumed during a given irrigation application cycle.

Effective Efficiency: A Water Use Efficiency Concept For Allocating Freshwater Resources

Andrew A. Keller and Jack Keller

Efficiency is “the ratio of the effective or useful output to the total input in any system.”

(*American Heritage Dictionary*)

The classical concepts of irrigation efficiency have been appropriate for farmers making irrigation management decisions and for planners designing irrigation conveyance and application systems. But applying classical efficiency concepts to water basins as a whole leads to incorrect decisions and, therefore, to faulty public policy. The critical difference is that in managing irrigated fields or designing an irrigation system, the total input is the amount of water that farmers must order or designers must handle, but that is not true for a water basin as a whole. As water flows through a basin, it may be used many times. Consequently the total input for each use-cycle is only the water that is effectively consumed.

Classical efficiency concepts systematically ignore the return flows from any given application of irrigation water. If, for example, the (classical) irrigation efficiency is 50% (ignoring leaching requirements), that means 50% of the water delivered is lost to the atmosphere through crop evapotranspiration. But what happens to the other 50%? The answer is, of course, that most of it flows to surface and subsurface areas. This return flow is usually captured by downstream pumps and diversions and reused. That is, one user’s inefficiency can be the next users’ supply of water. When the water is reused, the overall basin-wide efficiency increases. Thus, the irrigation system as a whole can be much more efficient than any of its parts.

A new concept, which we call *effective efficiency*, captures the effects of both recycling and changes in water quality¹ that occur during each use-cycle or a sequence of use-cycles. In this discussion, we focus on irrigation efficiencies and the degradation of freshwater resources resulting from salt concentration and salt pick-up or loading. We call the effective water use efficiency of an irrigation system, or the effective irrigation efficiency, E_e .²

Classical Irrigation Efficiency

The irrigation literature contains many classical efficiency terms. The basic concept of irrigation efficiency, I_e , was set forth by Israelsen (1950) as the ratio of the irrigation water consumed (evaporated) by crops, U_{ci} , to the irrigation water delivered from a surface or groundwater source to the canals or farm headgates, V_D :

Andrew A. Keller and Jack Keller are vice president and chief executive officer, respectively, Keller-Bliesner Engineering, Logan, Utah. The authors are grateful for the support of the Ford Foundation and Winrock International.

$$I_e = \frac{\text{Irrigation Water Evaporated by Crops}}{\text{Water Diverted, Delivered, or Applied}} = \frac{U_{ci}}{V_D} = \frac{\text{CropET} - P_e}{V_D} \quad (1)$$

where CropET is the crop transpiration and evaporation or evapotranspiration, ET , and P_e is the effective precipitation. This early definition, which has been accepted by irrigationists worldwide, is an appropriate but limited parameter for irrigation design. It applies only to the quantity of water that must be handled (pumped, conveyed, etc.) to accommodate an estimated amount of beneficial use. For design purposes, it is limited because it omits the necessary leaching water.

As irrigation water is transpired by crops and evaporates from the soil surface, salts remain behind and accumulate in the soil. To maintain a favorable salt balance for optimum crop production, these residual salts must be periodically leached from the soil by applying excess water. The ratio of the minimum amount, V_{LR} , of the applied irrigation water (in excess of $\text{CropET} - P_e$, or U_{ci}) that must pass below the crop root zone to maintain a favorable salt balance is called the leaching fraction or requirement, LR :

$$LR = \frac{V_{LR}}{U_{ci} + V_{LR}} \quad (2)$$

The leaching requirement is specific for each combination of irrigation water quality and crop because crops differ in their tolerance to soil salinity. It is also a function of the type of irrigation application system, the frequency of irrigations, and to a limited extent soil texture. Fortunately, the leaching requirement for different crops and irrigation water qualities has been well researched and documented (Ayers and Wescot 1985), so we will only consider the leaching requirement for typical surface and sprinkler irrigation application methods.³

Consequently we expand the classical concept of irrigation efficiency in equation (1) to account for leaching requirements (and we designate expanded classical efficiency as E_i):

$$E_i = \frac{I_e}{(1 - LR)} \quad (3)$$

or

$$E_i = \frac{(\text{CropET} - P_e) + V_{LR}}{V_D} = \frac{U_{ci} + V_{LR}}{V_D} = \frac{U_{ci}}{(1 - LR)V_D} \quad (4)$$

Figure 1 shows a schematic view of an irrigation project supplied by diverting water from a river. The relative locations of the data (terms) needed for computing the classical irrigation efficiency, E_i , by equation (4) are also included on the figure.

Irrigationists have struggled with the classical irrigation efficiency concepts and tried to tackle such problems as:

- how to deal with application uniformity, effective rainfall, and estimating actual crop evapotranspiration
- what besides evapotranspiration and meeting the leaching requirement is a legitimate beneficial use

- how to deal with practical values for conveyance losses, application uniformities, leaching requirements, meeting evapotranspiration potentials, and irrigation frequency and scheduling

Most recently, the American Society of Civil Engineer's Irrigation and Drainage Division Task Committee's draft report *Irrigation Efficiency and Distribution Uniformity*⁴ (dated 10 June 1994) suggests a new application efficiency term, *irrigation sagacity (IS)*:

$$IS = \frac{\text{Irrigation Water Beneficially and Reasonably Used}}{\text{Irrigation Water Applied}} \quad (5)$$

Beneficial uses include such items as crop evapotranspiration, leaching, germination, temperature and humidity control, and soil preparation. *Reasonable uses* include water needed to maintain drainage water quality, some deep percolation due to nonuniformity and uncertainties in salt management, and various losses that may not be economical to avoid.

Using irrigation sagacity (equation 5) provides an interesting approach for system design and a more realistic efficiency concept for evaluating irrigation systems because it justifiably includes beneficial and reasonable uses in addition to crop evapotranspiration and the leaching requirement. Its authors developed the irrigation sagacity concept out of concern that irrigation is

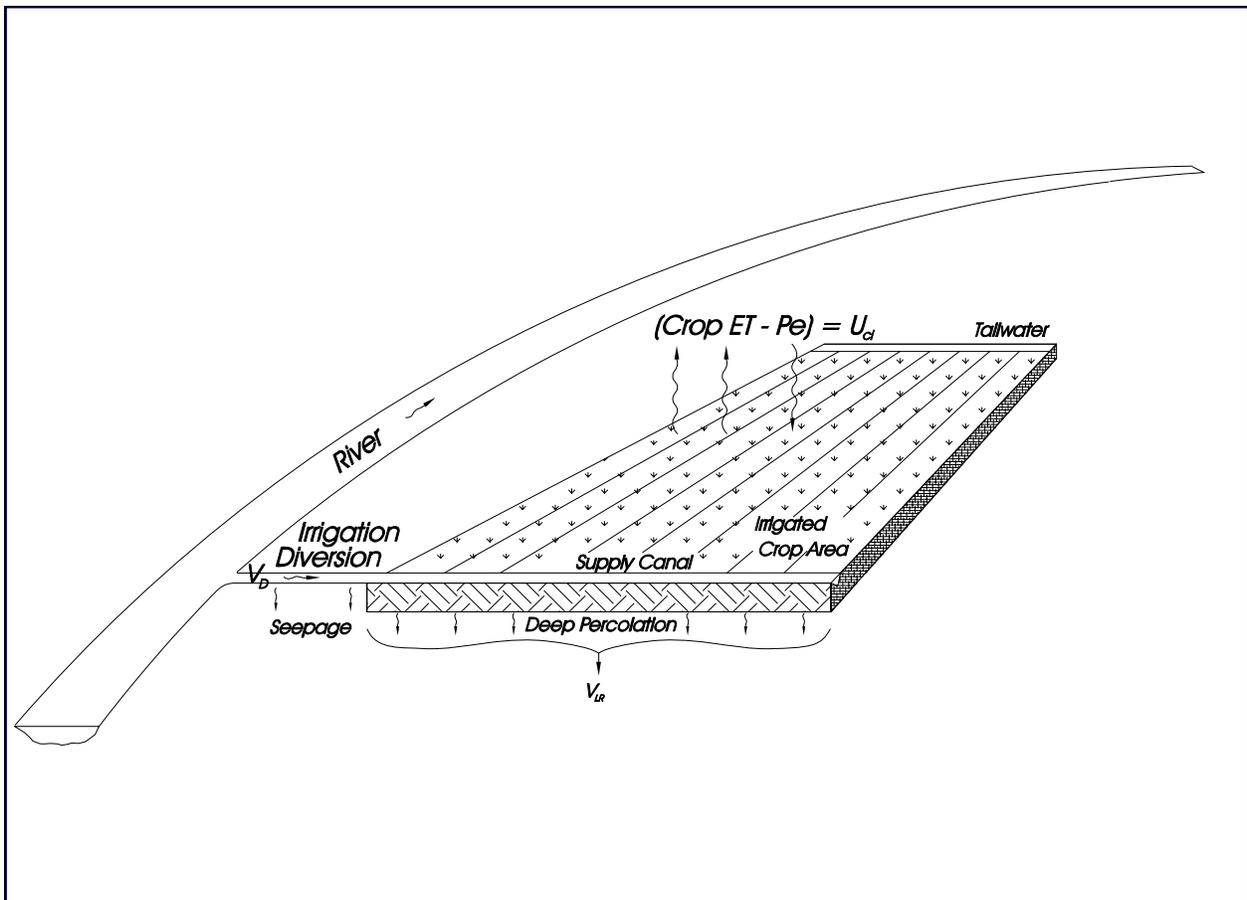


Fig. 1. Schematic view of a diversion project, and terms necessary for defining classical irrigation efficiency.

gaining a reputation of being inefficient and a water waster. Yet, irrigation sagacity, while it may put farm irrigation efficiency in a better light, is still a classical irrigation efficiency concept. It includes desired deliverables and reasonable irrigation water inputs, but it ignores reusable return flows. In other words, irrigation sagacity still makes irrigation appear to be a less efficient user of freshwater resources than it actually is. Therefore irrigation sagacity should not be employed for water resource allocation purposes.

The Water Multiplier Effect

In the early phases of planning irrigation development, the main concern is optimizing the system design with little attention to placing a value on the quantity of freshwater consumed. The genesis of the classical equations was the designers' needs for irrigation efficiency terms based on the ratios of desired outputs or deliverables to the required inputs. However, classical efficiencies were not meant to measure freshwater utilization. But they have often been misapplied and used for evaluating local or micro-level irrigation performance in the context of global or macro-level river basin planning.

Water quantity and quality changes must be related to time and location as the water flows through its basin toward its ultimate salt sink(s). We can structure our thinking around the conceptual differences between two types of water basin systems, those with the potential for multiple use-cycles and those where only one use-cycle is economically practical. Multiple use-cycle systems are systems where seepage, excess percolation, and operational spillage, which are often thought of as losses, can be economically reused in the same part or in another part of the system. For such systems, because of multiple reuse the supply of water to the basin can be much less than the total (aggregate) amount of water actually diverted or pumped from groundwater for use within the basin. In Keller et al. 1990, David Seckler called this the *water multiplier* effect.

Because of the multiplier effect, the global efficiency of a multiple use-cycle system is much higher than the classical efficiency of the individual use-cycles. The water multiplier is regulated not only by the quantity of evaporation but also by the quality of the water related to each use-cycle. Thus the interaction between efficiency and salinization/pollution is an important consideration. As long as salinity/pollution is not limiting, there is opportunity to select the most cost-effective mix of actions to either improve localized efficiency or to enhance reuse of residual waters.

The emphasis of water conservation for multiple use-cycle systems should be on the interplay between freshwater quality, use, and its potential reuse. This involves the interactions among the localized efficiency in individual water use-cycles, the salinity that builds up in the residual seepage and spilled water resulting from depletion and salt loading, pollution from waste water, and the reuse of the residual waters by recycling drainage and waste water and by conjunctive use of groundwater.

Single use-cycle systems (or parts of a system) are systems where there is limited potential for reuse of the spillage. This occurs where the spillage becomes too saline or polluted for economic reuse, where it is too expensive to recapture or relift, or where there is no opportunity to use it before it reaches a salt sink. For such uni-cycle systems (or uni-cycle portions of multi-

cycle systems), water conservation efforts must focus on improving localized water use efficiency because the global efficiency is the weighted average efficiency of the individual parts of the system.

Real Water Savings

In the western United States, early attempts to stretch water supplies by increasing irrigation application and conveyance efficiencies were unsuccessful and gave rise to the term “paper water.” It 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 irrigated a larger area using the apparent water savings, they increased their depletion at the expense of return flows relied upon by downstream users. In many instances, 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 were no real water savings.

As a result of these experiences, state engineers (who are responsible for water rights allocations in their jurisdictions) in the western United 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 to separate real water savings (often referred to as wet water) from paper water, or dry water, especially where major water transfers are involved.

E_i , classical efficiency, is a necessary parameter for determining the design capacity of the components of an irrigation system. However, it is not generally appropriate for measuring or identifying opportunities for real water savings and allocating water resources.⁵ E_i lacks linkage to the global scale and does not provide a basis for considering the ramifications of salt concentration and salt loading. It is very possible to make “improvements” to an irrigation system that increase its classical efficiency but that result in no real water savings.

Effective Irrigation Efficiency

Jensen (1977) and Jensen et al. (1980) aptly point out that the classical efficiency concept is commonly misapplied in resource development because the recovery of the irrigation water is ignored. For resource management purposes, Jensen (1977) suggests using net irrigation efficiency, E_n :

$$E_n = I_e + E_r(1 - I_e) \quad (6)$$

in which I_e is Israelsen’s irrigation efficiency (equation 1) and E_r is the fraction of the water that is not evaporated and can be recovered. However, equation (6) does not take into account leaching requirements or the effects of salt buildup in return flows.

The concept of effective efficiency and the associated concepts of effective supply and use overcome the limitations of the classical efficiency approach and equation (6). It provides a meaningful and useful tool to bridge micro and macro planning perspectives and to incorporate water quality implications in the strategic search for real freshwater conservation opportunities.

The amount of the actual water supply that can directly satisfy beneficial consumptive use is the effective supply. As implied above, irrigation water that is consumed by evaporation and

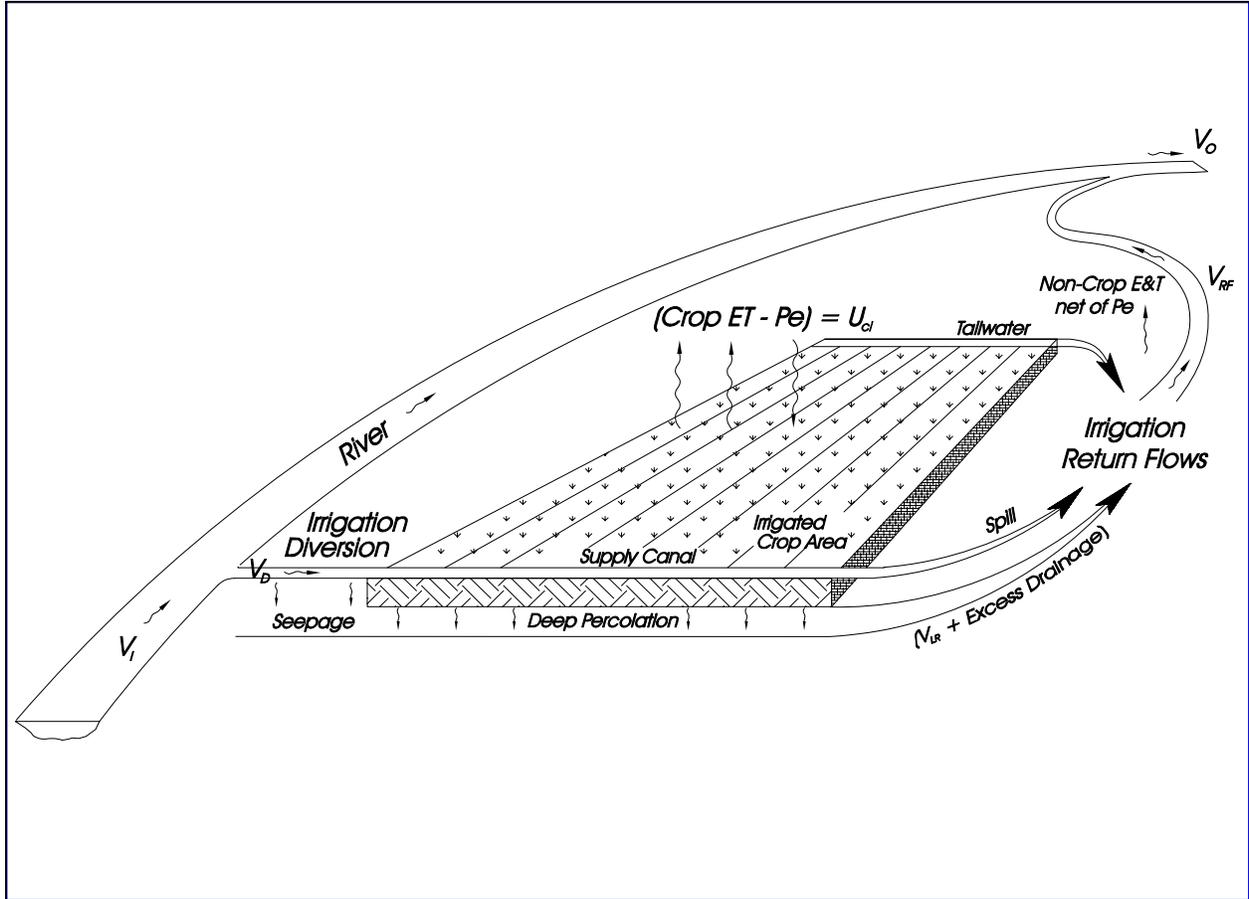


Fig. 2. Schematic view of a diversion project, and terms necessary for defining effective irrigation efficiency.

crop evapotranspiration leaves the remaining water more concentrated with salts. Some fraction (leaching requirement, LR) of the irrigation water supply must percolate through the root zone to hold soil salinity at an acceptable level. The more saline the water supply and the more sensitive the crop mix is to salinity, the greater the LR . The effective supply, V_e , is equal to the actual water supply, V , discounted for the LR :

$$V_e = (1 - LR)V \quad (7)$$

The actual water use, U , for a region is the difference between the inflow to the region and the recoverable or reusable outflow from the region. Likewise, the effective water use, U_e , for a region is the difference in its effective inflow, V_{ei} , and effective outflow, V_{eo} .

We define the effective irrigation efficiency, E_e , as the crop consumptive use of the applied irrigation water, U_{ci} , divided by the effective use, U_e :

$$E_e = \frac{U_{ci}}{U_e} = \frac{U_{ci}}{V_{ei} - V_{eo}} = \frac{\text{CropET} - P_e}{(1 - LR_i)V_i - (1 - LR_o)V_o} \quad (8)$$

Table 1. Comparison of classical and effective irrigation efficiencies for the Grand Valley and Imperial Irrigation District on the Colorado River in the USA and the Nile Valley irrigation system in Egypt.

	Grand Valley ¹		Imperial Irrigation District ²		Nile Valley
	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	
Inflow					
Water, V_i (ha-m/yr)	486,000	486,000	353,600	340,600	5,320,000
Salt (ppm)	573	573	629	629	250
LR using inflow, LR_i	13.6%	13.6%	15.1%	15.1%	5.5%
Effective supply, V_{ei} (% of inflow)	86.4%	86.4%	84.9%	84.9%	94.5%
Irrigation diversion (% of inflow)	14.2%	12.1%	100.0%	100.0%	67.3%
Net consumptive use ⁴					
Cropland, U_{ci} (% of inflow)	3.2%	3.2%	61.0%	63.4%	26.2%
Phreatophytes (% of inflow)	1.7%	0.5%	4.5%	4.2%	2.1%
Total (% of inflow)	4.9%	3.7%	65.5%	67.5%	28.3%
Irrigation return flow					
Water (% of inflow)	9.3%	8.4%	34.5%	32.5%	39.0%
Salt (ppm)	2268	1563	2506	2506	462
Recoverable (% of return flow)	100%	100%	0%	0%	100%
Outflow					
Water, V_o (% of inflow)	95.1%	96.3%	0%	0%	71.7%
Salt (ppm)	739	648	—	—	365
LR using outflow, LR_o	18.2%	15.6%	—	—	8.2%
Effective outflow, V_{eo} (% of inflow)	77.8%	81.3%	0%	0%	65.8%
Effective use, U_e (% of inflow)	8.7%	5.2%	84.9%	84.9%	28.7%
Efficiency					
Classical, E_i	26.0%	30.4%	71.9%	74.6%	41.2%
Jensen's net or effective, E_n	64.9%	86.0%	61.0%	63.4%	92.6%
Effective, E_e	36.8%	61.7%	71.9%	74.6%	91.3%

1 Extracted from Walker, Skogerboe, and Evans 1979 and Evans, Walker, and Skogerboe 1983.

2 Based on averages for 1985-1989 from the annual recapitulation of the Imperial Irrigation District's drain flow and canal flow, delivery, and spill data.

3 Based on hydro-salinity balances presented in Keller 1992.

4 Net consumptive use equals consumptive use minus effective precipitation.

where the subscript I denotes an inflow and the subscript O an outflow. In other words, it is the efficiency of an irrigation system expressed in terms of the amount of water effectively consumed by the system.

Like figure 1, figure 2 shows a schematic view of an irrigation project supplied by diverting water from a river, but with the relative locations of the data (terms) needed for computing E_e by equation (8). The striking difference between E_i and E_e computed by equations (4) and (8), respectively, is emphasized by comparing figures 1 and 2. The elements missing in the classical efficiency concepts are the return flows—from canal seepage and operational spills—and the tailwater and excess deep percolation from irrigation applications.

Comparing Classical and Effective Efficiencies

A comparison of classical, net, and effective irrigation efficiencies demonstrates their differences and the advantage of using E_e for freshwater resource planning and allocation decisions. We applied equations (4), (6), and (8) to two irrigated areas where water conservation

projects have resulted in real water savings—the Grand Valley in the Upper Basin of the Colorado River and the Imperial Irrigation District, which is supplied from the Lower Basin (table 1).

In the Grand Valley, the conservation objective was to diminish the salt loading of return flows that contribute substantially to the salinity of the Colorado River and thus reduce the effective supply to downstream users. The salt loading results from seepage and deep percolation water that flows through the saline strata underlying the valley before returning to the river.

In the Imperial Irrigation District (IID), which is near the terminus of the Lower Basin, the objective of current interventions is to achieve real water savings through a set of conservation projects funded by the Metropolitan Water District of Southern California (MWD). The IID/MWD Conservation Agreement specifies that a quantity of water equivalent to IID’s “real conservation water savings” can be diverted out of the Colorado River Basin to serve MWD’s (mostly urban) users along the Pacific Coast. Although the Colorado River water is fully allocated, diversions equivalent to the real water savings will not jeopardize the river’s existing water users.

Table 1 also includes the valley portion of Egypt’s Nile River irrigation system. This is an excellent example of a multiple use-cycle system with a high global efficiency but low local efficiencies. Egypt is interested in expanding the area irrigated by Nile River waters without reducing the high productivity of the present irrigated areas. To accomplish this will require an aggressive conservation program. However, directing conservation efforts toward areas where multiple use-cycles are possible, and thus E_e is already quite high, will result in little real water savings. The U.S. Agency for International Development is sponsoring a research project to identify areas and strategies that have the potential for yielding real water savings.⁶

Grand Valley Conservation Project

The water supply serving the Lower Colorado River Basin carries approximately 10 million metric tons of salt each year. Thirty-seven percent of this salt load is picked up by the irrigation return flow from agriculture in the Upper Basin. Studies have shown that almost 18% of this upper basin salinity comes from the 25,000 hectares (60,000 acres) of irrigated agriculture in the Grand Valley of western Colorado (Walker, Skogerboe, and Evans 1979).

The Colorado River Basin Salinity Control Act⁷ was enacted to mitigate salinity increases resulting from the exercise of water allocation rights in the upper basin. This law did not amend or conflict with the provisions of the Colorado River Compact or any other compacts or agreements allocating the waters of the Colorado River.

In our analysis we computed the classical, net, and effective efficiencies for both the pre- and post-conservation project conditions. We obtained the basic data for the computations from water and salt budgets given by Walker, Skogerboe, and Evans (1979) and Evans, Walker, and Skogerboe (1983). The results of the analysis are presented in table 1.

Pre-Project Conditions

The following are the steps for computing the effective, net, and classical irrigation efficiencies:

1. The water supply (from the Colorado River) for the Grand Valley irrigation system (GVIS) has an average salinity of 573 ppm (table 1). At this water quality, the inflow leaching requirement, LR_i , for

the typical crop mix is approximately 13.6%.³ This results in an effective available supply or inflow, V_{ei} , into the Grand Valley reach of the Colorado River (fig. 2) of $100\% - 13.6\%$, or 86.4% of the actual inflow, V_i .

2. Moving downstream just below where GVIS's irrigation return flows rejoin the Colorado River at the lower end of the Grand Valley, the salinity in the river increases to approximately 739 ppm. There the outflow leaching requirement, LR_o , is about 18.2%. This gives an effective outflow, V_{eo} , of 81.8% of the actual outflow, V_o .
3. Based on steps 1 and 2, the U_e for the GVIS is 86.4% of the flow in the Colorado River above GVIS's diversion minus 81.8% of the flow in the river below the point where GVIS's return flow enters it. The volume of water evaporated or actually used, U , within the GVIS is 4.9% of the total flow of the Colorado River at that location (based on the assumptions that irrigated crops served by the GVIS deplete 3.2% of the water supply and that the associated evaporation and phreatophyte consumptive use deplete an additional 1.7%). Since all of the return flow from the GVIS reappears in the Colorado River at the lower end of the Grand Valley, the effective use is calculated: $U_e = (86.4\% \times 100\%) - 81.8\% \times (100\% - 4.9\%) = 8.7\%$.
(In addition to the actual depletion of 4.9% by evaporation and evapotranspiration within the GVIS, an extra 3.8%, that is, $8.7\% - 4.9\%$, of the river's freshwater is effectively lost due to salt concentration and loading. Only a small fraction of this equivalent freshwater depletion results from the concentration of salts left behind after depletion by evaporation and evapotranspiration. Most of it is due to the salt pickup in the return flows.)
4. Based on the above values, the effective irrigation efficiency of the GVIS under pre-project conditions is $E_e = 3.2\% / 8.7\% = 36.8\%$.
5. If we do not consider the water quality impact and its effect in terms of the equivalent freshwater depletion, we obtain Jensen's net efficiency, which for GVIS under pre-project conditions is $E_n = 3.2\% / 4.9\% = 64.9\%$.
6. To compute the classical irrigation efficiency for the GVIS under pre-project conditions, we divide the 3.2% of the river's water that was consumed by the crops plus the required leaching volume, V_{LR} , by the irrigation diversion (table 1). First determine that $U_{ci} + V_{LR} = U_{ci} / (1 - LR) = 3.2\% / (100\% - 13.6\%) = 3.7\%$. Then the resulting classical irrigation efficiency is $E_i = 3.7\% / 14.2\% = 26.0\%$.

The Project and Post-Project Conditions

Optimization studies of salinity control strategies in the Grand Valley (Walker, Skogerboe, and Evans 1979; Evans, Walker, and Skogerboe 1983) showed that the most effective program (salt load reduction per unit cost) was to:

- Reduce canal seepage by lining all the lateral canals and 60% of the main canals with concrete
- Reduce on-farm (deep percolation and runoff) losses by 40% by sponsoring a set of on-farm conservation practices that included head ditch lining, gated pipe, and cutback furrow irrigation, for surface irrigation systems, sideroll sprinkler irrigation systems, and trickle irrigation systems

These interventions resulted in a total annual water savings of 5,830 hectare-meters and salt load reduction of 382,800 metric tons. This is equivalent to a reduction in effective use from 8.7% of the Colorado River inflow to 5.2% for an annual real freshwater savings of 17,000 hectare-meters. The classical irrigation efficiency, E_i , of the Grand Valley was increased by only 17% (from 26.0% to 30.4%), but the effective irrigation efficiency, E_e , was increased by almost 70% (from 36.8% to 61.7%) (table 1).

The classical efficiency could have been raised by reducing surface return flows from operational spills and farm tailwater. This would have decreased the total Grand Valley irrigation diversion by 32% and resulted in an increase in the E_i to over 41%. However, since the surface return flows come back to the Colorado River at essentially the same salinity level as the irrigation diversions, such interventions to increase the classical efficiency would result in essentially no real water savings and no change in the E_e .

Imperial Irrigation District Conservation Program

The set of conservation projects being implemented throughout IID's irrigation service area under the IID/MWD Conservation Agreement are expected to produce 13,100 hectare-meters (106,000 acre-feet) of real water savings. The fixed and operational costs of these conservation projects are being covered by MWD in exchange for the right to divert 13,100 hectare-meters of water from the Colorado River to the Los Angeles Basin. The implementation of the program is entering its sixth year and appears to be progressing on target.

The IID service area overlays a salt sink and is in the Imperial Valley, which drains directly into the Salton Sea. Therefore, the irrigation return flows become too salty for agricultural reuse. Unlike the Grand Valley, which is at a multi-cycle location in the Colorado River basin, the Imperial Valley is at a uni-cycle location. Since the classical "water losses" that become the return flows cannot be reused for irrigation, $E_e = E_i$, and we only need to consider the terms shown in figure 1 for computing them.

Pre-Project Conditions

The conditions prior to the IID/MWD conservation interventions are presented in table 1. We have treated the inflow of 353,000 hectare-meters that is delivered to IID as 100% of the imported inflow to the Imperial Valley because this represents a trans-basin diversion.⁸ Because there are no recoverable return flows, $E_i = E_e = 71.9\%$. The reason that E_n is lower (61.0%) is that the leaching requirement is not considered (as part of the beneficial use).

Post-Project Conditions

The conservation projects under the IID/MWD Conservation Agreement have been selected for their potential to reduce seepage and operational losses at the least cost per unit of water saved. The projects were not selected on the basis of whether the savings resulted from direct spills or seepage, because in either case the return flows are lost to salt sinks. The program is made up of the following generic types of projects:

- Concrete lining of most lateral and some main canals to reduce seepage losses
- Providing additional operational flexibility so that irrigators can more closely match the supply of water to on-farm demand
- Remote control, communication, and automation for main system structures plus additional off-stream storage to reduce main system operational losses.
- Cross-laterals at the ends of the regular delivery laterals to intercept the ordinary operational spills from them and convey the water to holding reservoirs from which it is diverted and reused in other parts of the system

- On-farm conservation practices that include promotion of improved irrigation scheduling, tail water recovery for surface irrigation systems, and trickle irrigation systems

When the IID/MWD conservation projects are completed, it is anticipated that the average diversions from the Colorado River to IID will be reduced by 13,100 hectare-meters. However it is also expected that the average beneficial crop water use (and crop productivity) will remain the same as under pre-project conditions. Thus, the classical and effective irrigation efficiencies will be increased from 71.9% to $E_i = E_e = 74.6\%$ (table 1).

Egypt's Nile Valley Irrigation System

Water released from Egypt's High Aswan Dam has an average salinity of about 250 ppm. At this water quality, the inflow leaching requirement is about 5.5% for the typical mix of crops grown in the Nile Valley. Thus the effective water supply or inflow to the upper end of the valley is 94.5% of the 5,320,000 hectare-meters per year released from the dam. The salinity in the Nile River at the lower end of valley is about 365 ppm, which gives an outflow leaching requirement of 8.2% and an effective outflow of 91.8% of the actual outflow.

Based on our preliminary estimates using the global water and salt balances presented by Keller (1992), the actual water use within Egypt's Nile Valley Irrigation System, NVIS, is 28.3% of the Aswan releases (its inflow) and the effective water use is 28.7% (table 1). The small difference of 0.4% between the actual and effective freshwater use or depletion within the valley is due to the increased concentration of salts. The increase is mainly the result of the actual depletion by evaporation and evapotranspiration, which leaves the salts behind, but the seepage and drainage flows that return to the Nile River carry very little additional salt. Thus, essentially no salt loading occurs, which is very different from the Grand Valley irrigation system where salt loading was a major concern because it caused the original effective irrigation efficiency to be very low.

Our estimate for the classical irrigation efficiency for the NVIS (using the procedure outlined in step 6 for the pre-project conditions in the Grand Valley and data from table 1) is $E_i = (26.2\% / 94.5\%) / 67.3\% = 41.2\%$. Thus it might appear that there is considerable opportunity for conserving water by reducing what appear to be water losses in the NVIS. However, there is actually little opportunity for saving water because the effective irrigation efficiency for the NVIS (based on the values for cropland use, U_{ci} , and effective use, U_e) is $E_e = 26.2\% / 28.7\% = 91.3\%$, which is already quite high. In fact to achieve any real water savings, either the cropland losses to evaporation, U_{ci} , or the losses to phreatophytes must be reduced, and this will be costly.

Conclusion

Classical water use efficiency concepts are appropriate for irrigation design and irrigation management, but they are ill suited for making decisions about water allocation and transfer policies. The classical efficiency concepts ignore the value of return flows. As a result taking steps to raise water use efficiency based on classical efficiency calculations often do not result in real water savings. However, many planners mistakenly justify and authorize irrigation improvement projects that are designed to improve a system's classical irrigation efficiency, E_i , expecting that this will generate real water savings. The savings exist mostly on paper, and the

mistake is compounded when “paper” water savings becomes the basis for expanding the area irrigated or authorizing water transfers (for example to urban users).

To overcome the limitations of classical water use efficiency, we have proposed a new concept, “effective efficiency,” for water resource decision making. Effective irrigation efficiency, E_e , takes into account both the quantity and quality of the water delivered from and returned to a basin’s water supply when estimating the total freshwater input for each use-cycle. Although we have focused on irrigation efficiencies in this paper, the effective efficiency concept can be applied to other uses of water and other measures of change in water quality or value.

Notes

¹ The effective depletion of freshwater resources results from changes in quality as well as quantity. The quantity is reduced by both evaporation and beneficial and nonbeneficial evapotranspiration. The quality of the remaining water is degraded because of salt concentration and salt pick-up or loading.

The effective efficiency concept can also be applied to other uses of water resources and other measures of change in water quality or value. Such changes might include changes in elevation, location, concentration of pollutants (heavy metals, sewage, chemical toxins), or flow rate.

² Subsequent to our first draft of this paper, we discovered that R. G. Allen and L. S. Willardson have been writing a paper, *Elimination of irrigation efficiencies* (to be presented at the 13th Technical Conference on Irrigation, Drainage and Flood Control, Sponsored by the U.S. Committee on Irrigation and Drainage, Denver, Colorado, October 19-22, 1994), pointing out that what we call classical irrigation efficiency is an outmoded term. They suggest that irrigationists stop using irrigation efficiency terms because the use “is interfering with rational management and planning of the use and allocation of water resources.” They recommend the use of ratios or fractions instead because classical irrigation efficiency terms, which do not consider reuse of return flows, have been misapplied so often (as pointed out by Jensen 1977). In their presentation of the use of ratios in place of efficiencies, they consider the degradation of water due to salt build up and pollution, and consider the need for leaching. Although we do not necessarily agree with eliminating the use of the efficiency concept, we applaud their crusade to correct the misunderstanding of classical irrigation efficiency terms.

³ The leaching requirement (LR) for typical surface and sprinkler irrigation application methods is calculated: $LR = EC_w / (5EC_e - EC_w)$, where EC_w is the electrical conductivity of the irrigation water and EC_e is the electrical conductivity of the soil saturation extract for a given crop and tolerable degree of yield reduction (available from tables of crop salt tolerance). For this paper we have assumed an allowable EC_e of 1.5 mmhos/cm. If the soil salinity is maintained at this level or lower through adequate leaching, most crops would experience no yield reduction. Beans, which are highly salt sensitive, would suffer about a 10% yield reduction at this EC_e . To convert parts per million (ppm) to mmhos/cm we have assumed a constant of 640 ppm per 1.0 mmhos/cm.

⁴ The committee is chaired by Charles Burt and has the following active members: Albert Clemmens, Fedja Strelkoff, Leland Hardy, Dean Eisenhower, Terry Howell, John Merriam, Ron Bliesner, Larry Dawson, and Kenneth Solomon.

⁵ The only time it is appropriate is for areas overlying saline soils or groundwater where the return flows become too saline for reuse.

⁶ Strategic Research Program, Water Research Center, sponsored by the United States Agency for International Development, Environmental and Natural Resources Policy and Training Project.

⁷ Public Law 93-320 enacted June 24, 1974.

⁸ The Imperial Valley is not part of the Colorado River Basin though water is diverted to it through canals and without tunneling or pumping.

References

- Ayers, R. S., and D. W. Westcot. 1985. *Water quality for agriculture*. FAO Irrigation and Drainage Paper No. 29 (Rev. 1). Rome: FAO.
- Evans, R. G., W. R. Walker, and G. V. Skogerboe. 1983. Strategies for salinity control for the Upper Colorado River Basin. *Transactions of the ASAE* 26(3): 738-42, 747.
- Israelsen, W. O. 1950. *Irrigation principles and practices*. 2nd ed. New York: Wiley.
- Jensen, M. E. 1977. Water conservation and irrigation systems. In *Proceeding of the Climate-Technology Seminar*, 208-50. Columbia, Missouri.
- Jensen, M. E., S. Harrison, H. C. Corven, and F. E. Robinson. 1980. The role of irrigation in food and fiber production. In *Design and operation of farm irrigation systems*, ed. M. E. Jensen, 15-41. ASAE Monograph No. 3. St. Joseph, Michigan: American Society of Agricultural Engineers.
- Keller, J. 1992. *Implications of improving agricultural water use and efficiency on Egypt's water and salinity balances*. Center for Economic Policy Studies Discussion Paper No. 6. Arlington, Virginia: Winrock International.
- Keller, Jack, N. S. Peabody, III, David Seckler, and Dennis Wichelns. 1990. *Water policy innovations in California: Water resource management in a closing water system*. Center for Economic Policy Studies Discussion Paper No. 2. Arlington, Virginia: Winrock International.
- Walker, W. R., G. V. Skogerboe, and R. G. Evans. 1979. Optimization of salinity control in Grand Valley. *Journal of the Irrigation and Drainage Division (ASCE)* 105(IR1): 15-28.

