ELIMINATION OF IRRIGATION EFFICIENCIES

L.S. Willardson, R.G. Allen, and H.D. Frederiksen[1]

Question 47
Irrigation Planning and Management Measures
in Harmony with the Environment

13th Technical Conference, USCID
Denver, Colorado
October 19-22, 1994

ABSTRACT

The idea of irrigation efficiency has been used to evaluate water management for many years. The need for new water management policies no longer permits the use of the concepts and generalizations found in irrigation efficiency definitions. In order to understand the effect of different types of water use, consumptive and extensive, on basin water supply management, new ways of describing and evaluating water use are needed that take into consideration the physical truths and realities of what are now called "irrigation efficiencies". The advent of computer models capable of including the effects of various kinds of water use, including their effect on water quality, make it possible to holistically manage water, provided the criteria used are properly understood. New definitions are proposed that require re-naming irrigation efficiencies to various types of "fractions" including consumptive fraction, reusable fraction, and non-reusable fraction.

INTRODUCTION

The concept of irrigation efficiency has served the needs of irrigated agriculture for a considerable period of time. When irrigation engineers began to look for ways to improve irrigation, the use of irrigation efficiency terms became important to allow quantified comparisons to be made between irrigators and between irrigation methods. As long as there was adequate fresh water for new users, low or high efficiencies were simply measures of the way water was being used on a farm. The original efficiency term was called "duty of water" and was expressed as the quantity of water required to grow a particular crop. Wilson (1912) defined the duty of water as "the ratio between a given quantity of water and the area of crop which it will mature." It was recognized that sandy soils required more water than clayey soils and that long canals required more water than short canals. Duty of water was reported in terms of the acres that could be irrigated by one cubic foot per second or in terms of acre feet per acre required for irrigation.

A few years later, Israelsen (1932) applied the engineering concept of efficiency to

---

[1] Professor, Dept. Biol. & Irrig. Engrg., Utah State Univ., Logan, UT, U.S.A.; Assoc. Professor, Dept. Biol. & Irrig. Engrg., Utah State Univ., Logan, UT, U.S.A; Principal Water Resources Engineer, Env. & Nat. Res. Div., The World Bank, Washington, D.C.

First published in 1994.

irrigation on single fields. His definition was based on the water used by the crop divided by the water applied. Many types of efficiencies describing irrigation water use were developed (Willardson, 1959; Jensen, 1967; Bos, 1985, Jensen, 1993) and used as measures of irrigation system performance. The idea of "efficiency" has even been suggested for application to the uniformity of distribution of irrigation water over a field (Keller and Bliesner 1990).

The general engineering definition of efficiency is an output divided by an input, both of the same character. Implicit to this definition is that any difference between the output and input constitutes a "loss" to the process in both a physical and an economic sense, such as heat generated from an automobile engine which is dissipated to the atmosphere. However, use of the term "efficiency" in irrigation evaluations ignores the true disposition of the water not consumed by the crop. Nonconsumed (nonevaporated) water is rarely dissipated in a non-recoverable or non-reusable form by irrigation. Therefore, the nonconsumed component of applied irrigation water is not a "loss" to the total resource, but is potentially reusable. The common definition of efficiency, as applied to irrigation, produces values that are now being interpreted by many non-engineers and engineers alike as water lost to the hydrologic system. Engineers must be careful to use universally understood concepts and language common to the public and to those who make the decisions that are fully understood by the bureaucracy that formulates legislative proposals and implements decisions, in order to avoid misunderstandings.

A new term is needed that will clearly describe the impact of a given water use on the actual physical losses of utilizable water from the affected hydrologic system. The term must (a) be appropriate for evaluating water allocation, water use, and related management options, (b) be consistent and appropriate for all users, not just for irrigation and for a narrow evaluation of irrigation practices, and (c) be clearly understood in concept and in terms that can be correctly applied by any person engaged in the water allocation/use/management debate. Application of such a term would clarify what the allocations of water to various uses at various locations in hydrologic system actually mean in terms of the total water supply.

Since the sustainable or renewable supply of global fresh water, for any use, is now seriously recognized as being finite, use of the term efficiency to describe water use is no longer appropriate. New ways must be found to describe the management and use of water that take into account the unique behavior and recycling of water and its importance to all forms of life on the planet, including both positive and negative effects of water use on the environment. Unless the ideas now associated with irrigation efficiency terms are modified, it will be extremely difficult to properly manage the world supply of fresh water due to the misconceptions and misunderstandings of irrigation efficiency by the engineering, political, and news communities. Use of the term "efficiency" suggests that increasing irrigation efficiency will result in a larger supply of fresh water being available. However, this is not the case. This misconception stems from the notion, brought about by use of the term efficiency, that losses from irrigation are not recovered and reused and that all improvements in water management will increase the net water supply downstream. The current literature contains many recommendations to increase irrigation efficiencies to create more available water (UN-FAO News Release, Feb/94; Yaxin and Guangyun, 1993). The economic damage and waste of limited water resource management funds caused by such articles and misconceptions is very large.

It is now timely to change the perspectives of evaluation of water use to include all uses and to determine the effect of each use, in a global context, on the recoverability or return, for reuse, of diverted water. There are some hydrologic systems where nearly one hundred percent of the water is being used productively. Reuse in such cases cannot be increased nor can be altered practices in such a project yield additional water to be used by downstream diverters. Use of the term "irrigation efficiency" has caused an absolute dichotomy between the physical situation of the hydrologic system and the public's and government's perception of the physical nature of water management. These incorrect views are so pervasive and strongly held that millions of dollars are proposed for investments to correct the deficiencies while the public actually believes that their nation's water problems are being solved. The public has been convinced that selected investments and penalties on irrigation would free up vast amounts of water for other uses. The perception is that improvements in irrigation efficiencies can meet all the nation's future water needs. Only a fully rational approach to water management can minimize the conflicts that arise between municipal, industrial, environmental, recreational, aesthetic, and agricultural uses of the finite fresh water supply. New ways of evaluating water use are needed and the terms used to describe water use will have to be changed.

RATIONAL WATER MANAGEMENT

The advent of computers and the development of modeling techniques to describe physical and chemical processes related to water movement, above, on, and under the surface of the soil, have made it possible to evaluate the effects of upstream water use on downstream water supplies. It is commonly understood that any use of water causes a change in the physical and chemical condition of the returning or remaining water. The hydrologic cycle, figure 1, is well known even to students in elementary schools. The normal representation of the hydrologic cycle does not, however, have any indication of the changes in quantity, quality, temporal availability, location, or elevation of the water as it travels from the place where the rain falls to the ocean. The effect of human use of water is not well represented. With adequate modeling, it is now possible to fill in the missing information on water disposition between the watershed and the ocean and to demonstrate the net effect of man's use of the water, regardless of whether it is extracted from surface streams or ground-water aquifers. Management must be done without resorting to gross classifications such as "irrigation efficiency."

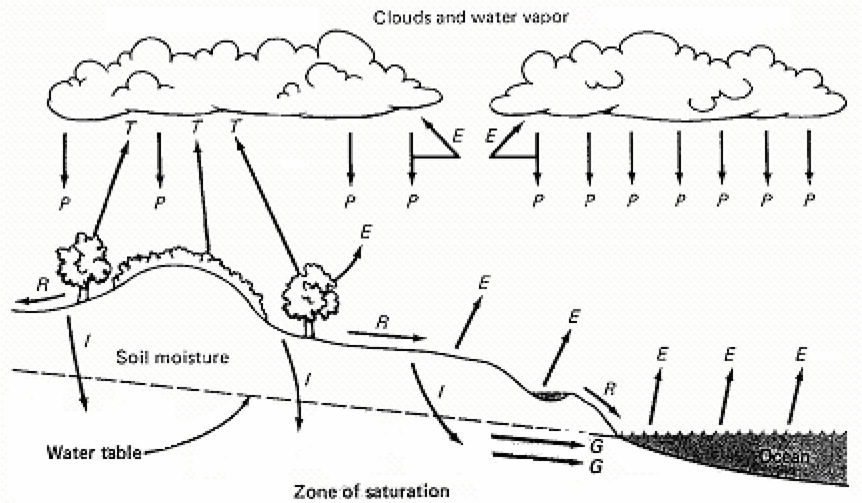

Figure 7 -1 The hydrologic cycle: 7: transpiration; *E,* evaporation; P, precipitation; *R,* surface runoff; G, groundwater flow; I, infiltration.

Figure 1. Hydrologic Cycle (from Viessman and Welty, 1985).

Every use of water has a physical cost in terms of either quantity or quality .Irrigation, for example, has a high physical cost in terms of quantity of water because a large part of the water applied to the soil for growing a crop is consumed and is returned directly to the atmosphere. A side effect of irrigation is a change in the quality of the water not consumed. The cause is usually not because irrigation adds salt to the water, but because the salt present in any water that was evaporated and transpired by plants is merely concentrated in the water that was not consumed. Use of water for cooling by industrial enterprises and power plants, including nuclear power plants, has precisely the same effect. Wetlands, established for the preservation of wildlife and environmental enhancement, have the same effect as irrigation on water quality and quantity; salt or nutrient concentrations increase due to less water remaining after evaporation.

One of the important uses of water is for sanitary waste disposal. When an individual washes his hands, for example, the quantity of the water he uses is changed very little and normally returns to a river system. However, the quality of the water may be substantially changed. It will now contain additional boron and phosphates if a detergent soap was used. It may contain bacteria and viruses from the person's skin and body. It may also be aesthetically undesirable in appearance. If the concept I II efficiency, as currently used in evaluating irrigation were applied here, with no acknowledgement of the returned fraction, hand washing would be extremely inefficient from a quantity standpoint, and would also be inefficient from a quality perspective. Efficiency is not an appropriate concept to apply to hand washing or to irrigation, due to the return of a substantial fraction of the water to the original or an alternate supply source in both cases.

An extreme example of wasteful and inefficient use of water was given by Fredricksen (1992). He pointed out that 80 to 90 percent of the water "used" by a large coastal city is discharged into the sea. In this case, the discharge does constitute a loss, since the return water becomes non-recoverable as fresh water. This translates into an equivalent use "efficiency" of 10 to 20 percent.

It is apparent that where nonconsumed (nonevaporated) water reenters the fresh water system, the quantity and quality of returning water should govern the evaluation of effectiveness of water use, not simply the ratio of consumed fraction relative to diverted amount, evaluated only on a local basis.

FRACTIONS IN PLACE OF EFFICIENCIES

Fractions are used in many applications to describe what proportion of some quantity has been used effectively. In an arid-area irrigation situation, a leaching fraction is used to estimate the actual amount of water passing through the root zone for salinity control. Use of a fraction evaluation instead of an efficiency prevents the occurrence of a serious logic error in describing or evaluating the management of water. Jensen (1993) discussed the need for a change in the ways that water use is described, and has also advocated moving away from the term efficiency.

In irrigation, use of "Consumed Fraction" (CF) instead of irrigation efficiency clearly identifies the proportion of the water applied that is consumed in the production of plant material. It is then possible to visualize and to more accurately determine the amount of water that is still hydrologically available for reuse. The fraction of the water that plants do not consume is either still flowing on the surface, or is moving in the soil profile to become part of a local or regional ground-water supply. Use of an efficiency instead of a more descriptive fraction term would suggest that if the irrigation were made more efficient, then water would be saved. However, in general, no water can be saved by increasing irrigation efficiency because no water is being lost. Unused water will, in approximately 95% of the cases, return to a supply in reusable form within the same locale or region, and is therefore available to be reused. This returning and reused component has historically been referred to as return flow. It can also be termed the "Reusable Fraction" (RF).

Project irrigation efficiencies in the United States are estimated to average 40 percent. Fredricksen (1992) estimated irrigation efficiencies to be 30 percent in the developing world. However, basin-wide consumed fractions for irrigation are estimated to average 87 percent (SCS, 1981) due to recovery of the reusable fraction. Increasing the irrigation efficiency, i.e. the consumed fraction, upstream may cause serious water quantity and quality problems downstream.

PROPOSED EQUATIONS FOR FRACTIONS

The following fractions are proposed for assessing some of the impacts of fresh water diversions by irrigated agriculture, municipalities, and industry, on water resources.

Consumed Fraction. The consumed fraction, CF, has nearly the same definition as traditionally used for irrigation efficiency. In simple terms, where no non-reusable losses occur, CF is defined as:

$$CF = \frac{Q_{ET}}{Q_{Div}} \tag{1}$$

where Q_{ET} is the quantity of crop evapotranspiration supplied by irrigation and Q_{Div} is the quantity of water diverted by the project. Units of Q_{ET} and Q_{Div} are expressed as equivalent depths or as volumes. Q_{ET} is sometimes termed the "net irrigation water requirement." The quantity (1 – CF) is the water potentially available for reuse.

Conveyed Fraction. The familiar term of conveyance efficiency can be replaced by the synonymous term "conveyed fraction", C_vF, which is defined within an irrigation project as:

$$C_vF = \frac{Q_{Del}}{Q_{Div}} \tag{2}$$

where Q_{Del} is water delivered by a project to fields and has the same units as Q_{Div}. The water not delivered and not consumed by evaporation or evapotranspiration along the delivery system is all potentially available for reuse.

Complete Definitions for CF. More complete definitions for CF are needed for larger scale management applications. At the project level, a project-level consumed fraction, CF_{proj}, is defined as:

$$CF_{proj} = \frac{Q_{ET} + Q_{NR-proj}}{Q_{Div}} \tag{3}$$

where $Q_{NR\text{-}proj}$ represents any "non-reusable" quantities of water, besides Q_{ET}, at the irrigation project level. $Q_{NR\text{-}proj}$ represents water which does not reappear in a water source in a recoverable condition, and includes diverted water which either flows to the ocean, to brackish water bodies, or to evaporation ponds via surface or subsurface flows, or evaporates from canals, reservoirs and seeps. $Q_{NR\text{-}proj}$ should be charged to the project as water consumed, since its non-recoverability or non-reusability is a direct result of the particular use. Units of Q_{ET}, Q_{NR}, and Q_{Div} in Eq. 3 are expressed as equivalent depths or as volumes.

A field-level consumed fraction, CF_{field}, must therefore be defined as:

$$CF_{field} = \frac{Q_{ET} + Q_{NR-field}}{Q_{Del}} \tag{4}$$

where Q_{Del} is water delivered to the field in the same units as Q_{ET} and Q_{NR}. $Q_{NR\text{-}field}$ represents non-reusable quantities of the delivered water in addition to the Q_{ET} at the field level.

Reusable Fraction. The reusable fraction, RF, represents the fraction of project diversions returning to a water source for sequential reuse by others. It is defined as:

$$RF = \frac{Q_{Div} - Q_{ET} - Q_{NR-proj}}{Q_{Div}} = 1 - CF_{proj} \tag{5}$$

Non-Reusable Fraction. The non-reusable fraction on a project level, NRF_{proj}, is defined as:

$$NRF_{proj} = \frac{Q_{NR-proj}}{Q_{Div}} \tag{6}$$

and the non-reusable fraction on a field level, NRF_{field}, is defined as:

$$NRF_{field} = \frac{Q_{NR-field}}{Q_{Del}} \tag{7}$$

The relative magnitude of NRF_{field} may be different than the project average value NRF_{proj} due to effects of location within an irrigation project. Generally, the non-reusable quantities of water for fields or conveyance systems in upper regions of irrigation projects are small relative to Q_{Del} and Q_{ET}, especially if hydrology and elevation promote convenient and timely reuse of water or return of water to the stream or to ground-water systems. NRF may be high for fields or conveyance systems near the lower portions of irrigation projects in situations where percolation or runoff enters the ocean or brackish water bodies.

Relationships among fractions. From Eq. 3 through Eq. 7, it is apparent that the following "mass balances" exist:

$$1 = CF + RF \tag{8}$$

and

$$1 = EF + RF + NRF \tag{9}$$

where EF represents the "evaporated fraction", defined as $EF = Q_{ET}/Q_{Div}$ on the project level and as $EF = Q_{ET}/Q_{Del}$ on the farm level. From Eq. 9:

$$CF = EF + NRF \tag{10}$$

which indicates that the true consumed fraction is comprised of both the fraction of water which is evaporated (via the evapotranspiration process) and the fraction of water which is made non-reusable for other subsequent beneficial use due to hydrologic or water quality constraints, or due to resource management or political directives.

Also,

$$Q_{Div} = Q_{ET} + Q_R + Q_{NR\text{-}proj} \tag{11}$$

where Q_R is the quantity of reusable water from the project (return flow). Uniformity terms such as distribution uniformity and coefficient of uniformity, which are used to describe the uniformity of water application within a field, do not need modification.

As indicated above, Q_{ET} is the net quantity of crop evapotranspiration requirement in excess of effective precipitation. Q_{ET} is computed as

$$Q_{ET} = ET_c - P_{eff} \tag{12}$$

where ET_c is total crop evapotranspiration and P_{eff} is effective precipitation. Effective precipitation is defined as the amount of natural precipitation retained within the crop root zone and used to fulfill a portion of the ET_c requirement. Generally P_{eff} is about 70 to 90% of total precipitation. P_{eff} is a part of the water management equation, but is in reality not very manageable. ET_c varies with crop type, length of growing season, and with climate. Units of Q_{ET}, ET_c, P_{eff} are expressed as equivalent depths or as volumes. If equation (11) yields a negative value, then there may be a net yield of water from the project to the water resources system, i.e., a negative extraction.

LOSSES

The term irrigation "losses", as applied to all water which is not evaporated or transpired, should be abandoned in lieu of a more descriptive and correct fraction term. All water delivered by irrigation which returns to a water source in reusable condition should be termed an "irrigation return" or "reusable fraction" and not an "irrigation loss". Irrigation returns include surface runoff and deep percolation components. Most deep percolation is not "lost", but is "returned".

It is estimated that 46 percent of water diverted for irrigation in the United States returns to a water source for future reuse (SCS, 1981; Solly et al, 1988). However, there are instances where non-recoverable losses do occur. These include situations where:

- Irrigation diversions are made directly upstream of oceans so that nonevaporated (non-consumed) fractions flow or seep into the ocean and are lost.
- Irrigation diversions where deep percolation enters brackish ground-water bodies or where surface and subsurface flows enter brackish surface water bodies (such as the Salton Sea of California, the Great Salt Lake of Utah, or the Dead Sea of Jordan and Israel).
- The nonconsumed fraction of water diverted for irrigation is converted into evaporation and transpiration by wetlands and riparian vegetation adjacent to drains, canals, ditch banks, or reservoirs. However, in many situations, evapotranspiration from wetland vegetation supports valuable wildlife habitat and is considered to be a beneficial use.

Magnitudes of non-reusable fractions from irrigated agriculture are estimated to be only 13 percent of the total U.S. irrigation diversions (SCS, 1981). The return fractions from irrigation diversions may average about 55% of total diversions worldwide (Fredricksen, 1992). Nearly all of this latter return fraction is reused as recharged ground-water or for downstream re-diversion.

In addition to irrigation, non-reusable quantities of water occur in other water resources uses. For example, water allocated to "wild rivers" in northern California is not recovered for any other use and runs directly into the ocean and becomes non-recoverable. Such water has a very low evaporated fraction but has a very large non-reusable fraction (and consumed fraction). Such uses of water should not be excluded, but the public should understand their impacts on total available fresh water in terms consistent with the description of all other uses. Water that is polluted with hydrocarbons and industrial chemicals may become a non-reusable fraction of the available water supply. If the non-reusable fraction of water from a particular use and the cause of non-reusability are identified, it may be possible to implement a more effective water management practice with a higher recovered and reused fraction. A low consumed fraction for a city high in a watershed permits a large fraction of the returning water to be reused downstream. A low consumed fraction in a large coastal city may result in nearly all of the sewage effluent (reusable under some circumstances) to become non-reusable when it is discharged directly into the ocean. Non-consumed water from irrigation will be non-reusable if it is mixed with excessively salty ground-water or surface water.

REUSABLE FRACTIONS

There are many benefits of low consumed fractions (CF) in irrigation projects which result in large reusable fractions and return flows. Many of these benefits are not readily apparent and therefore may be largely unappreciated. For example, The Yolo County WCFCD intentionally leaves its canals unlined in order to recharge the county's ground-water system. During the 1980's drought, when all surface supplies of water failed, this long-term ground-water storage saved their tree crops and maintained a quality water supply for the cities of Davis and Woodland. Benefits of low CF's include:

- Creation of wetlands. There are thousands of hectares of wetlands across the western United States which were nonexistent 150 years ago. These wetlands were created and are sustained by surface and subsurface returns from irrigation diversions upstream. Many of these wetlands are home to endangered species of plants and animals.
- Recharging ground-water bodies. A large portion of irrigation returns enter local or regional ground-water systems and form an important source of water for municipalities, industry and residences.
- Dampening extremes in stream discharges. Irrigation returns are of-diffused back to receiving streams throughout the year due to the slow movement of ground-water systems. Therefore, some returns augment stream flows during periods of low flow. In the western U.S., the majority of irrigation diversions are made during the months of April -July, which is usually the period of maximum stream flow, especially where the majority of stream flow is from snowmelt. Therefore, diversion of water by irrigation reduces stream discharges during flood stages, reducing flooding potential downstream. These increases in minimum discharges and reductions in maximum discharges of river systems also increase annual hydropower generation, navigation opportunity, minimum stream flows for fish habitat, and recreation opportunities.
- Reduction of excessive stream diversions. Water diversion with a delayed return of the nonconsumed fraction in regions with cold winters may limit the development, diversion and consumption of water by additional new irrigation projects during cropping periods, thereby insuring larger late season stream

flows below irrigated lands. Increasing the consumed fraction (irrigation efficiency) would actually reduce water in a stream for immediate diversion by other irrigation projects, and the net effect would be a larger volume of evapotranspiration by irrigated crops and a reduction of annual in-stream flow below the irrigated areas.

- Temporal Changes. An important benefit of low consumed fractions relates to temporal change in water resource availability caused by delayed return of reusable fractions. Such a change might be positive or negative. For example, irrigation projects in eastern Idaho have traditionally had low consumptive fractions. Irrigation "efficiencies" have ranged in the neighborhood of 12 to 40% (Allen and Brockway, 1983) and have been looked upon with disdain by politicians and environmentalists. However, these low efficiencies (now CF's) have been an extremely valuable asset to the southern Idaho economy. High springtime stream flows from snowmelt in the Snake River and Henry's fork are diverted to farms in eastern Idaho. These diversions, which have historically averaged about 10 billion m^3 (8 million AF) per year I store water in the soil profile and at the same time reduce flooding potentials downstream. Since the CF's are only about 30% on the average and there is limited runoff, a large fraction of the water diverted (approximately 70%) eventually enters ground-water systems via deep percolation through coarse soils. Local ground-water systems join the massive Snake Plain Aquifer system which flows 300 km from eastern Idaho toward south-central Idaho, discharging water back into the Snake River via springs along the way.

A majority of aquifer discharge back into the Snake River occurs in the Thousand Springs area near Hagerman, Idaho. The average annual discharge from springs this area has increased from 120 m^3 s^{-1} (4200 cfs) in 1900 to a high of 190 m^3 s^{-1} (6800 cfs) in 1952 due to irrigation development in eastern Idaho (figure 2). Aquifer discharge has decreased since 1955 due to irrigation well withdrawals from the aquifer by new sprinkler irrigation developments and some reduced recharge in eastern Idaho due to conversion of some surface irrigation systems to sprinkler. Discharge from springs constitutes a majority of late summer and fall flows in the middle Snake River below Thousand Springs.

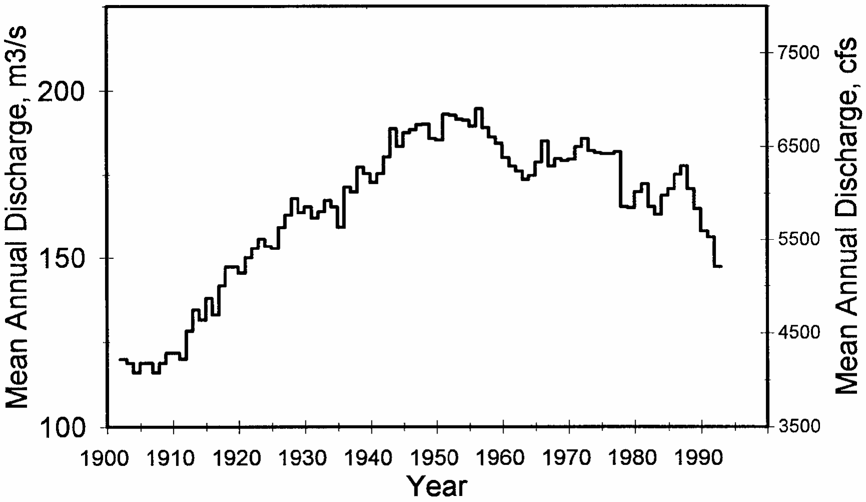

Figure 2. Mean Annual Discharge from Springs along the North Side of the Snake River between Milner and King Hill, Idaho (C.E. Brockway, 1994, Pers. Comm., Data

from USGS).

The benefits of irrigation-induced recharge to the Snake Plain Aquifer during the last century and the delayed discharge back into the Snake River have been important to the southern Idaho economy and include the following:

- World famous trout fisheries at "Thousand Springs" near Hagerman, Idaho. More than a dozen commercial fisheries along the Snake River near Thousands Springs produce 20,000 tons of blue ribbon rainbow trout (85% of the U.S. supply) each year, valued at $80 million. The water temperature of the Thousand Springs is a nearly constant 14 ^{o}C throughout the year and is sediment and disease free, perfect for trout production. In addition to commercial fisheries, three government-owned hatcheries raise steelhead smolts for augmenting populations of this endangered species in other parts of the Pacific Northwest.
- Hydropower production during late summer, fall and winter along the Snake River from Hagerman to the Columbia River has increased as a result of the increase in recharge to the Snake Plain Aquifer and a delay in the timing of the return to the Snake River system. A total of 550 m head is converted to electricity by power plants along the Snake River below Hagerman. Spring flows, which historically would exceed hydropower capacities during most years, are reduced by the high irrigation diversions (with low CF's) in eastern Idaho. This temporal displacement and storage has historically increased annual hydropower production by approximately 400,000 MWhrs worth $20 million, based on estimates by IDWR (1990). The Snake Plain Aquifer in effect functions as a huge, non-evaporating ground-water reservoir. The cost for an equivalent volume of storage capacity in terms of additional main stem reservoir storage would be enormous with substantial environmental, wildlife and aesthetic costs.
- Enhanced river flows below Thousand Springs during drought years due to the large storage capacity and buffering effect of the Snake Plain Aquifer.
- Flooding on the main stem of the Snake River and Columbia River has been reduced in spring months due to the large irrigation diversions in eastern Idaho.
- Reduced pumping lifts from the aquifer. The increased recharge of the nonconsumed fraction of irrigation diversions to the Snake Plain Aquifer has increased ground-water elevations along the Snake River Plain to various degrees. The increased elevations reduce pumping lifts-by farms which obtain water directly from the aquifer.
- Navigation potential on the lower Columbia River and lower Snake River during fall and winter months has been increased by the augmentation of low river flows during this period by Snake Plain Aquifer discharge.
- The aesthetics of the Thousand Springs along the Snake River Canyon near Hagerman attracts tens of thousands of visitors per year to the area. Lush flora attracts and fosters wildlife populations.

There have been some negative impacts by low CF's in eastern Idaho. These include enforced reductions in irrigation diversions by "junior" water right holders during late summer during some drought years, when all divertable water is taken by senior users. However, if diversions by junior users were allowed to increase by reducing diversion rates of senior users, then the CF of the region would increase in some years due to a higher total ET from irrigated crops in the region. This would impact water users downstream along the lower Snake and Columbia Rivers.

Other negative impacts of low CF's in eastern Idaho include reduced magnitudes of "flushing" flows in the Snake River during the high flow months in late spring. Large flushing flows have been investigated by federal agencies during the past few years to evaluate their effectiveness in transporting salmon and steelhead smolt through downstream reservoirs on the Snake River and Columbia River system. Reduced flooding and high flows on the Snake River have also changed some of the characteristics of riparian and benthic plant and animal communities.

In spite of the large benefits brought about by low CF's in the eastern Idaho region, politicians and other groups have often advocated that the dreadfully low irrigation "efficiencies" be increased. These demands have come about due to misunderstandings of the hydrology of the region and misconceptions related to use of the term "irrigation efficiency." The use of a consumed fraction would develop a clearer picture of water resource management needs. Reduction of irrigation diversions in eastern Idaho by reducing the "losses" of water would in reality often reduce diversions when water is in excess and reduce return flows when water is in shortage. The result would be a net decrease in the economic base of the area and region.

EFFECTS OF INCREASING CONSUMED FRACTIONS

It is agreed that, in general, increases in the consumed fraction of irrigation diversions and the resulting reduction in the reusable fraction have some benefits. These include the potential for reduced leaching of nutrients out of root zones, reduced waterlogging, smaller drainage requirements, reduced energy consumption, reduced conveyance system capacities, increased stream flow during irrigation periods, and the possibility of increased land areas irrigated per unit of water diverted from a particular point of diversion. However, none of these benefits include a reduction in "losses" of water.

As an example of some of the subtle complexities involved when attempting to increase the consumed fraction of irrigation diversions (in the name of increasing irrigation efficiencies), is the conversion from surface irrigation systems to more "efficient" sprinkler irrigation systems in the Colorado River basin in western Colorado and eastern Utah. This conversion has been encouraged by economic subsidies from the government (USBR, 1986; Hedlund and Shoemaker, 1993). The primary purpose for encouraging conversion from surface irrigation to sprinklers has been to increase "efficiencies" of individual farms to reduce deep percolation of water below farms so that less salt might be leached from the saline marine shale formation lying beneath the farms. The goal is to reduce salinity concentrations in the lower Colorado River. However, it is not clear that reduced deep percolation flux densities will reduce the total load of salt leached from the shale formation. Reduced deep percolation from irrigation may only reduce the dilution factor.

One of the side effects of the sprinkler conversions appears to run contrary to the stated goal of salinity reduction. Salinity levels in the lower Colorado could actually increase due to the conversions. If conversion to sprinkler irrigation does reduce deep percolation fluxes, then the certainty of irrigation supply and adequacy at the farm level will improve. The result of increased application uniformities with sprinkle irrigation and increased supply adequacy is better irrigation coverage over fields irrigated. The increased coverage increases total crop evapotranspiration (ET) by eliminating or reducing parts of fields previously underirrigated and overirrigated and therefore increases yields. The net effect is more total ET from the irrigated area. This in turn results in less total stream flow in the lower Colorado River with which to dilute the natural salt load in the river. If the relative increase in ET due to the conversion to sprinkler is greater than the reduction in total salt load from the irrigated region of Colorado and Utah, caused by the conversion, then the net effect of the conversion will be increased salinity levels (concentrations) in the lower Colorado system. This of course is contrary to the expressed purpose for the irrigation system conversion. Local farms in Utah and Colorado may be the only benefactors of the system conversions. Less total water may be left in the Colorado River for diversion by Arizona, California, and Mexico and it may actually have higher salinity levels.

An additional negative side effect of conversion to more "efficient" irrigation systems with higher consumptive fractions is that some wetlands in the region, which have been historically created and sustained by surface or local ground-water returns from surface irrigation, are drying up due to reduced return flow and reduced river diversions (Harris, 1993). The effects of increasing the CF of irrigation diversions must consider impacts on wetlands created by historically low CF's of irrigation systems.

The Colorado River Salinity Control Program is an important program. However for some phases there is a potential for many secondary effects and management issues to occur when the consumed fraction of irrigation diversions (irrigation "efficiency") is increased. Application of the concept of consumed fraction may help to illuminate some of these externalities.

CONCLUSIONS

Irrigation efficiency is an outmoded term that is interfering with rational management and planning for the use and allocation of fresh water resources. Irrigation efficiency, as defined and as currently understood and interpreted by decision makers, is unsuitable for formulating or instituting sound management of a country's water resources. Both practitioners and decision makers must apply common concepts to describe how various uses affect the quantity of water available in a given hydrologic system. Both must use terms common for all uses so they and the public can clearly understand and apply rational analyses to water allocation issues. Irrigation is no longer an endeavor isolated from others who either impose on or depend on fresh water resources. Decision makers cannot continue using terms that mean one thing to the irrigation sector and another fundamentally different thing in the common language as applied by the public and leaders in water management. The quantity impact of a given use should be in terms of (a) the quantity of water it directly consumes, and (b) the quantity, by virtue of that use, that is rendered unavailable to other users. Changing to the term "fraction" to describe water use will give the proper perspective to what is happening to water resources due to human interventions. If appropriate fractions are used to describe what is happening to water, positive as well as negative effects of various water uses can be identified. Use of Consumed Fraction, Reusable Fraction, and Non-Reusable Fraction will provide for better consideration of the effects of all users of water on other users in the same hydrologic system, and on the effects of return fractions to the streams or aquifers. Modeling, combined with fully quantified water use fractions, will be necessary to understand the short and long term effects of every water resource use.

REFERENCES

Allen, R.G. and Brockway, C.E. 1983. Operation and Maintenance Costs and Water Use by Idaho Irrigation Projects. p. 160-174 in Proceedings of the 1983 Specialty Conference on Irrigation and Drainage, Am. Soc. Civil Engrs., New York.

Bos, M.G. 1985. Summary of ICID Definitions on Irrigation Efficiency. ICID Bulletin, 34(1):28-31.

Drever, J.I. 1988. The Geochemistry of Natural Waters. 2nd Ed. Prentice-Hall. Englewood Cliffs, New Jersey. 437 pp.

Frederiksen, H.D. 1992. Drought Planning and Water Efficiency Implications in Water Resource Management. World Bank Technical Paper 185. World Bank, Washington, D.C. 28 pp.

Harris, R. 1993. How Federal Mandates to Protect Wetland resource Value Necessitates a Multi-agency Approach to Balance that with Other National Economic Goals. p. 178-182 in Proceedings of the 1993 National Conference on Irrigation and Drainage Engineering, ASCE, New York.

Hedlund, J.D. and Shoemaker, G.A. 1993. USDA Actions to Replace Wildlife Values Lost Due to Irrigation Improvements -Colorado Salinity Program. p. 183-190 in Proceedings of the 1993 National Conference on Irrigation and Drainage Engineering, ASCE, New York.

Hoffman, G.J., Maas, E.V., Pritchard, T., and Meyer, J.L. 1983. Salt Tolerance of Corn in the Sacramento-San Joaquin Delta of California. Irrig. Sci. 4:31-44.

Idaho Department of Water Resources. 1990. Memorandum Decision and Order on Evaluating Effects of Development of New Irrigated Acreage on the Snake Plain Aquifer. IDWR, Boise, ID, 5 p.

Israelsen, O.W. 1932. Irrigation Principles and Practices. John Wiley and Sons, New York. 418 p.

Jensen, M.E. 1967. Evaluating Irrigation Efficiency. J. Irrig. and Drain. Div., Am. Soc. Civil Engr. 93(IR1):83-98.

Jensen, M.E. 1993. Impacts of Irrigation and Drainage on the Environment. Fifth Gulhati Memorial Lecture. Proc. 15th ICID Congress. The Hague, Netherlanas.

Keller, J. and Bliesner, R.D. 1990. Sprinkle and Trickle Irrigation. van Nostrand Reinhold. New York. pp. 99-115.

Snake River Technical Advisory Committee. 1983. Needed Water Resources Programs in the Snake River Basin. Idaho Water and Energy Resources Research Institute, University of Idaho, Moscow, ID. 75 p.

Soil Conservation Service. 1981 America's Soil and Water Condition and Trends. Washington, D.C.

Solly, W.B., C.F. Merk, and R.R. Pierce. 1988. Estimated Use of Water in the United States in 1985. U.S. Geological Survey Circular 1004. Denver Colorado.

United States Bureau of Reclamation. 1986. Colorado River Water Quality Improvement Program, Uinta Basin Unit Planning Report, Environmental Impact Statement, Appendix B, Hydrosalinity.

Viessman, W. Jr. and Welty, C. 1985. Water Management Technology and Institutions. Harper and Row, New York. 618 p.

Willardson, L.S. 1959. Characterizing Water Use by Means of Efficiency Concepts. Paper #59-204. Am. Soc. Agr. Engrs. Summer Meeting.

Wilson, H.M. 1912. Irrigation Engineering. 6th edition, pp. 47-57. John Wiley and Sons. New York.

Yaxin, C, and N. Guangyun. 1993. The Evaluation of Irrigation Efficiency and a Water Saving Strategy for Hetao, China. ICID Bulletin. Vol. 42, No.2. pp. 11-21.

GLOSSARY

ET_c	Total crop evapotranspiration
P_{eff}	Effective precipitation
Q_{Div}	Quantity of water diverted from surface and/or ground-water sources
Q_{Del}	Quantity of water delivered to project farms or fields
Q_{ET}	Quantity of evapotranspiration from crops, in excess of effective precipitation (net irrigation water requirement)
Q_{NR}	Quantity of water, besides Q_{ET}, which is not reusable from surface or ground-water sources
Q_R	Quantity of diverted water which is reusable from surface and ground-water sources (return flow)

Fractions

CF	Consumed fraction
C_vF	Conveyance fraction
EF	Evaporated fraction (beneficial ET from agricultural crops)
NRF	Non-reusable fraction
RF	Reusable fraction

Lyman Willardson

Lyman Willardson is an agricultural engineer and has served as a consultant on more than 65 irrigation and drainage projects (both international and domestic). He has written over 200 publications related to irrigation, drainage, and salinity control. He has conducted more than 41 years of research on irrigation and drainage and has coordinated more than 25 research projects. He has taught over twenty-one years of graduate and undergraduate courses on drainage and irrigation. He is currently Professor Emeritus of the Department of Biological and Irrigation Engineering at Utah State University.

Harald D. Frederiksen

Harald Frederiksen is a consultant in water resources management. His recent clients include the World Bank, ADB, IDB, IWMI and governments and international consultants in South America, the Middle East and Asia. His assignments have included assistance with institutions, financial issues and strategy for water resources management; privatization of urban services; national and basin resources management and draft water laws. He serves on the ASCE committee to draft generic water laws for two forms of U.S. rights. From 1984 to 1995, Mr. Frederiksen worked with the World Bank, eight years of which he was Head of the Water Resources Unit providing technical support on water resources matters to Operating Departments in the Bank’s South and East Asia Regions. He has also served on various Bank policy and program committees and authored several Bank Technical Papers on institutions, drought planning, and basin water accounting. From 1967 to 1984, he served as President of Frederiksen-Kamine Associates and rose to Executive Vice President and Manager of D&R Corp managing services in international development and related fields of agriculture, engineering, resources planning and agency organization in Afghanistan, Bolivia, Brazil, Caribbean, Iran, Jordan and Venezuela and in the US. The prior eight years he spent in planning, design and construction of the California State Water Project. Mr. Frederiksen received a BSCE Utah State University and a MSCE from the Univ. of Minnesota and is a Fellow American Society of Civil Engineers, Member of the International Commission of Irrigation and Drainage, and Associate Member of the International Association for Water Law. He has authored numerous papers in journals and presented at international workshops and conferences on issues in the field.

R.G. Allen

RICHARD G. ALLEN is a Professor of Water Resources Engineering at the University of Idaho. He is active internationally in development of measurement and prediction tools for evapotranspiration, crop water requirements and irrigation water management. He was coeditor of the ASCE Practices Manual 70 Evapotranspiration and was an author of the United Nations Food and Agriculture Organization Irrigation and Drainage publication No 56: "Evapotranspiration and Crop Water Requirements". Allen has authored 190 research and professional publications and has served as an expert consultant to the United Nations, World Meteorological Organization, United States Agency for International Development, and governments of Portugal, Morocco and Spain. He has served twelve research and teaching missions to developing countries and has collaborative research ties with scientists in the Netherlands, Portugal, Belgium, France, Spain and Italy. He has served as an expert in water rights cases in California, Florida, Utah, Colorado, Kansas, Nebraska and New Mexico. Allen holds a B.S. in Agricultural Engineering from Iowa State University, M.S. in Agricultural Engineering from University of Idaho and Ph.D. in Civil Engineering from University of Idaho. Allen has 30 years experience in research and teaching and has been a member of engineering faculties at Iowa State University, Utah State University (1985-1998) and University of Idaho (1998 - present).