Water Conservation Questions and Definitions from a Hydrologic Perspective

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Abstract

Water conservation activities are frequently encouraged within municipalities and irrigation systems, especially during periods of drought. The objectives of many irrigation water conservation programs have been to increase irrigation efficiencies with the expressed purpose of reducing gross diversion requirements. The intent during droughts is that less water will be depleted from a limited resource. In long-term conservation programs the intent is that more water will be made available for other users. However, the reasons for reducing diversion requirements must have both a regional and local interpretation from a hydrologic and conservation of mass viewpoint. Water management principles used to guide society's water use objectives require terms and definitions that clearly describe the effects of various water uses, both consumptive and non-consumptive, within a hydrologic system. Some water use terms such as the evaporated fraction, reusable fraction, nonreusable fraction and consumed fraction are discussed in this paper. These terms are useful to both users and public in developing improved, rational and visual understandings of the hydrologic nature and impacts of water use and conservation programs.

In situations where the nonevaporated components of irrigation diversions return to the fresh water resource for reuse by others, conservation programs may not stretch water supplies or "save" water in the region, especially in the long-term, and especially where the initial source is from ground-water. In some instances, where water is abstracted from streams, irrigation water conservation programs can actually be "ET sustainment" programs, since they may sustain a more "consumable" water supply for one city or project at the potential expense of downstream projects, cities and perhaps the environment. Water conservation programs should fundamentally be evaluated in the context that, in general, the only real loss of water from an irrigation project is by the process of evaporation from open water surfaces, evaporation from moist soil and transpiration from vegetation. Fundamental hydrologic concepts and questions are described that can help planners and managers to establish the context and impact of individual conservation programs in the near and long term.

Introduction

In irrigation systems where return flows reenter a fresh water resource and are of reusable quality, water is only saved over the long run through water conservation where the evaporation or evapotranspiration (ET) components are reduced. However, issues of stream flow reduction and time lags can be important. In cities, the investments in costs for treatment of water and distribution capacity, degradation of ground-water must be considered in addition to when or whether excess water applied returns to a fresh water resource for reuse. Conservation programs may not save "real" water, but only change the distribution of the resource in space and time. In these cases, the public investment is not well spent. Some water use

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terms such as the evaporated fraction, reusable fraction, non-reusable fraction and depleted fraction are discussed that can help the user and the public develop improved visual understanding of the hydrologic context and true impacts of water use and conservation programs. Fundamental questions are provided to help quantify the context of the water conservation program and the impacts from a hydrologic viewpoint.

Appropriate Reasons to Conserve Water by Increasing "Efficiency" (Uniformity) of Water Application

The following are appropriate reasons why cities or irrigation projects or systems should conserve water:

- Reduce costs for treating water
- Reduce costs for pumping water
- Reduce costs for added distribution capacity in an area of growing population or demand
- Reduce leaching of fertilizers and other chemicals and degradation of ground-water
- Sustain flows in specific segments of streams that are threatened by low flows or thermal increases and where "nonevaporated" components of diverted water bypass the stream or return at a less valuable time
- Where "nonevaporated" components of diverted water flow into a saline system (ocean, saline lake, or brackish groundwater) and are therefore nonrecoverable or contaminate streams downgradient.
- Where water is abstracted from a deep, confined aquifer, but the "nonevaporated" components of abstracted water percolate to a more shallow unconfined aquifer, thus changing the distribution of water between the aquifers in an undesireable way.

In agriculture:

- Reduce waterlogging and improve salinity control
- Enhance equity among users
- Maximize the total fraction of water delivered to crops to increase crop yields
- Reduce soil erosion.

Inappropriate Reasons to Conserve Water by Increasing "Efficiency" (Uniformity) of Water Application

The following are inappropriate reasons to initiate a water conservation program:

- To create "new" water downstream in regions where return flows (from nonevaporated diversions) already reenter the water resource at an appropriate time
- To enhance streamflows for long distances downstream where return flows (from nonevaporated diversions) already reenter the water resource at an appropriate time
- To extend the life of an unconfined aquifer where return flows (from nonevaporated diversions) already reenter the aquifer with acceptable quality

Benefits of Low Efficiencies

The following are benefits of low efficiencies of water application (i.e., overirrigation or poor distribution uniformities) that are realized in a number of situations (Allen et al., 1997). These benefits are fortuitous and are not usually designed as part of water management:

- Recharge to unconfined aquifers
- Dampening of flood flows or redistribution of flows over time (due to reentry of return flows with some time lag and dampening)
- Augmentation of streamflows during droughts (due to reentry of return flows created by diversions during periods of higher flow). The augmentation of diffusive return flows by groundwater may help cool streamflow and benefit biota
- Incidental ground-water recharge near oceans may help reduce salt-water intrusion
- Creation of wetlands

Fundamental Precepts

There are fundamental precepts that govern the ability to conserve water and the ability to create “new” water by a conservation program. These are:

- The law of Conservation of Mass. The Law of Conservation of Mass suggests that matter can not be created nor destroyed. In the context of liquid water, the law suggests that liquid water, while remaining as liquid water (and not evaporated) can not be created nor destroyed. Thus all nonevaporated components must be “somewhere” and must reappear “somewhere.”

- The reality that 99% of the earth’s landmass is underlain by ground-water (Freeze and Cherry, 1979) impacts the “loss” of water. All deep percolation “losses” are not “lost” to the hydrologic system, but seep downward vertically to the groundwater. After entering the saturated groundwater system, the liquid moves with the groundwater laterally, at some velocity determined by hydraulic gradient and geology, until it discharges to a surface water source.

Thus, the only way to really create “new” water is to reduce the water that is degraded to the point where it is not usable by anyone else downstream or to reduce the evaporated component of the diversion (i.e., reduce the evapotranspiration, ET).

The above appropriate reasons for conservation programs are all valid reasons and goals for water conservation efforts, but they should be worth the price paid to obtain them. Many improvements may not conserve water on a regional basis, since ET of irrigated lawns or fields is normally not reduced in these types of "conservation" programs. In fact, ET may actually be increased due to improved uniformity and more careful control of water application. Therefore, water conservation efforts on the local scale may ultimately increase water consumption both on a local and regional scale.

Reality and Efficiency

The primary consumption of water within an irrigation system is by the process of evaporation from open water surfaces, evaporation from moist soil and transpiration from vegetation. The combination of this evaporation and transpiration is termed ET. In addition to ET, water that is returned to a saline water body or that is severely degraded in quality is essentially lost as a freshwater resource. All other water diverted by an irrigation system remains in liquid form and will ultimately return to a freshwater system. The return of diverted water to the system is a natural, diffusive process that is nearly impossible to control, because remaining liquid water must obey the law of gravity and the law of conservation of mass. Gravity brings nonevaporated water back to a stream, ocean or aquifer system.

The term irrigation efficiency (IE) has traditionally been defined as the ratio of the sum of beneficial consumption and leaching to gross diversions. (Jensen, 1967; Bos, 1985). Unless the ideas now associated with the implications of low irrigation efficiency are modified, it will become extremely difficult to properly manage the supply of fresh water in arid regions of the world due to the misconceptions and misunderstandings by the engineering, political, and news communities. For example, much current irrigation literature contains erroneous recommendations to increase irrigation efficiencies in order to create more available water some distances downstream (for example, UN-FAO News Release, 1994; Yaxin and Guangyun, 1993; U.S. Water News, 1995). The economic damage and waste of limited water resource management funds caused by such articles and misconceptions is large.

There are hydrologic systems where nearly one hundred percent of the water is being productively consumed due to natural reuse within the system. Total consumption in such cases cannot be increased past 100%, nor can altered practices designed to "increase irrigation efficiency" in such a system yield additional water to be used by new diverters without reducing the consumption (i.e., evaporation) of current users. Use of the term "irrigation efficiency" has caused a 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 pervasive and strongly held. Billions of dollars have been proposed for investment to correct for low irrigation efficiencies with the intent that water problems will be solved. The public has been convinced that selected investments and penalties imposed on irrigation will free up vast amounts of water for other uses. 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.

Importance of Local Hydrology and Location within a River Basin

Some irrigation projects are located close to the ocean or directly upstream of other saline water systems such as saline lakes or saline ground water sinks. In these situations "return" flows from irrigation projects enter these saline systems and are truly lost for additional consumption by humans. In these situations, reducing diversions by enacting water conservation programs may allow upstream users to divert and consume more water, thereby increasing the total beneficial consumption of the water resource.

In areas where excess diverted water percolates through soil profiles and picks up salt, return flows from deep percolation increase the total salt load of the receiving water resource and may reduce its economic usefulness. In these cases, reducing diversions and return flows by increasing irrigation uniformity and reducing excessive applications may increase the effective water supply.

Basic Hydrology and Law of Conservation of Mass

There are saturated ground-water bodies lying beneath the earth's surface almost everywhere in the world. These ground-water bodies have had thousands of years to develop, and have built up to an equilibrium point so that ground water flows freely by gravity, if it is unconfined, to a lake or stream system (or to the ocean, if nearby) where it discharges. Unless they have been overdrafted by pumping, most ground-water systems are in equilibrium with surface water systems. Most streams exist during periods of low surface runoff because a ground-water table feeds the stream. The addition of water to a ground-water system is, over the long term (perhaps tens of years or less), balanced by similar amounts of outflow to a surface system. The flow process is controlled by gravity, is automatic, and is inevitable, i.e. part of the basic hydrologic equilibrium.

A consequence of reducing water diversions is almost always a reduction in return flow back to the resource. Therefore, the quantity of net consumption by an irrigation system may be largely unchanged by a conservation program. To effectively create "new" water in a regional context, unless directly upstream of a salt sink, a conservation program must in some way reduce evaporation or ET or improve return flow quality, and not simply reduce diversions. Reductions in the direct consumption of water are usually in the form of reducing areas of phreatophytes or wetlands along canals, collection ditches, or in areas of shallow, ground-water seepage to the soil surface. Wetlands and phreatophytes created by irrigation are often considered to be of value for wildlife habitat and may be lost when water conservation practices are implemented. Reduction of crop ET will almost always reduce turf quality or crop yields, unless evaporation from soil is reduced without reducing plant transpiration.

It is important that irrigation improvement procedures be evaluated to show when and how water is actually saved by the conservation program. Guidelines for preparation of conservation plans must include procedures for describing hydrologic components and interactions within and beyond irrigation system boundaries, with descriptions and examples of how to assess whether evaporation or ET can be reduced within the system or "return" flows into saline systems can be reduced, thereby achieving real conservation of water and the creation of an enhanced water supply. Unfortunately, it is common to draw "lines" around system boundaries and to neglect the real interconnections between in-system "losses" and existing river system gains.

Definition of Water Consumption Terms

An improved, graphic image of the hydrologic and basin-wide effects of irrigation is possible when the disposition of water within an irrigation project is described in terms of "fractions." Definitions based on fractions have been proposed by Jensen (1993), Willardson et al. (1994), Allen et al. (1996, 1997) and Molden (1997) and Molden and Sakthivadivel (1999) for assessing the impacts of fresh water diversions by users of water resources, including irrigated agriculture, municipalities, industry, and ecological interests.

The new terms are intended to encapsulate clearly the impact of any and all types of water use on actual physical losses of utilizable water from the affected hydrologic system. Unlike most efficiency terms, the proposed methodology and terms (a) are appropriate for evaluating water allocation, water use, and related management options, (b) are consistent and appropriate for all water uses, not only for irrigation and a narrow evaluation of irrigation practices, and (c) can be clearly understood conceptually and in terms that can be correctly applied by people engaged in the water allocation / use / management debate. Application of such terms will help to clarify what the allocation of water to various uses at various locations in a hydrologic system actually means in terms of the total water supply.

A change from using "efficiencies" to using "fractions" to describe water use eliminates many misunderstandings. Fractions are used in many applications to describe what proportion of some quantity has been applied to a particular use. 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 use of the term efficiency in irrigation.

Figure 1 shows a matrix of uses and disposition of irrigation diversions categorized as beneficial and nonbeneficial and as consumptive and nonconsumptive as described by Clemmens et al. (1995), with enhancements to the water disposition categories by Allen et al., (1996, 1997). The figure illustrates relationships among the following fractions proposed to describe the hydrologic disposition of irrigation diversions. The fraction terms are defined as follows:

Evaporated Fraction.

The evaporated fraction (EF) is the fraction of an irrigation diversion that is consumed through evaporation or evapotranspiration:

$$EF = \frac{Q_{ET}}{Q_{Div}} \qquad \mathbf{1}$$

where Q_{ET} = quantity of diversion consumptively evaporated (or transpired) by the water use process (for example, irrigation) and Q_{Div} is the total diversion of water to the specific process. Besides ET from landscapes or cropped fields, Q_{ET} includes evaporation from evaporation ponds, canals, reservoirs and seeps, and water evaporated from riparian vegetation and wetlands created by irrigation return flow or seepage. EF is similar to the irrigation consumptive use coefficient term introduced by Jensen (1993), except that EF may also include evaporation external to the primary process.

Nonreusable Fraction

The nonreusable fraction (NRF) is defined as the fraction of a diversion that is not evaporated, but is no longer available for reuse by other water users due to entry into a saline system (ocean, brackish water bodies, or saline aquifers) or due to degradation in quality to the point that it is economically nonresuable, or is physically beyond economic recovery:

$$NRF = \frac{Q_{NR}}{Q_{Div}} \qquad \mathbf{2}$$

where Q_{NR} = quantity of diverted water that is still in liquid form, but has been made nonrecoverable due to the physical manipulation by the user (diverter). The NRF represents the fraction of Q_{Div} that could conceivably be made available to other users, in addition to reductions in nonbeneficial ET, through conservation efforts, without reducing crop yields. Nonrecoverable water that results from a particular use should be identified and charged to that use.

Consumed Fraction

The consumed fraction is defined as the fraction of total diversions that are consumed, i.e., no longer available to any other user during any future time period. The consumed fraction includes the evaporated fraction and the nonreusable fraction, since physically, these two fractions are "consumed" in the context of the fresh water resource. The consumed fraction (CF) includes any water exported from the basin:
where Q_{exp} = water that is exported to outside the hydrologic basin. An example is water contained in

$$CF = \frac{Q_{ET} + Q_{NR} + Q_{exp}}{Q_{Div}} \approx EF + NRF \qquad \mathbf{3}$$

fresh fruit that transported from a basin, or in the case of production of bottled water or other beverages, the water contained in the beverage, assuming that the beverage is not consumed within the basin.

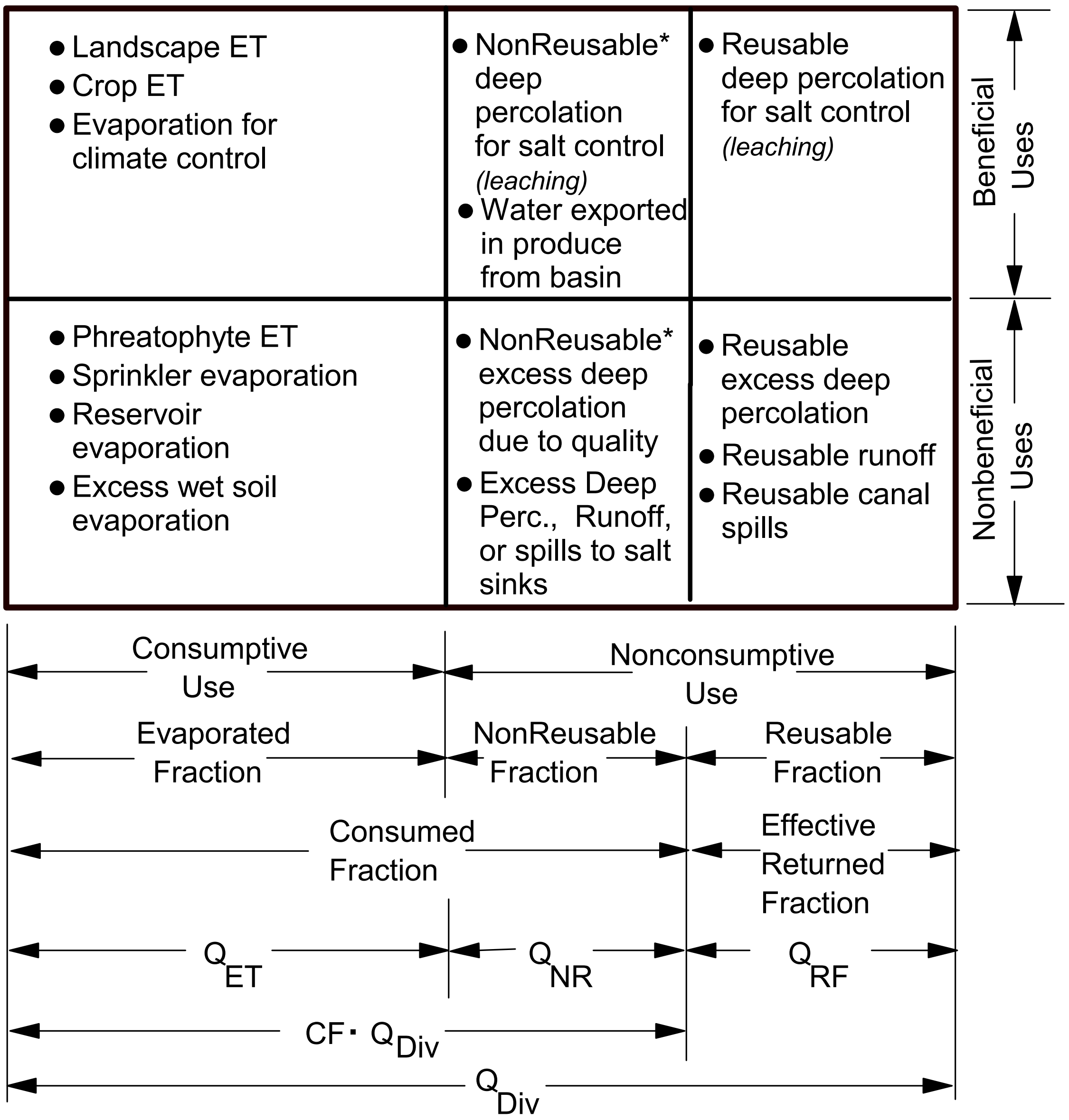
In the definition of consumed fraction, the term "consumed" means that the CF fraction of the diversion is truly consumed or otherwise transformed so that it is no longer reuseable by any other future user within the basin. The consumed fraction of diversions either undergoes a phase change (evaporation), is exported outside the basin, or enters a nonreusable state due to extreme salinization pollution, or uneconomically recoverable location, any of which make the water nonreuseable by anyone else. It is important that the reader realize fully that water diverted by an irrigation project or any other user is not "consumed" unless one of the transformations occurs (transformation from liquid to vapor or entry into a nonreuseable quality state). The user should be considered responsible for the quantity of the water resource which, on a basin-wide scale, is the product $CF \bullet Q_{Div}$.

Reusable Fraction

The reusable fraction (RF) represents the fraction of the diverted water that returns to the water resource for subsequent reuse by others:

$$RF = \frac{Q_{RF}}{Q_{Div}} \qquad \mathbf{4}$$

where Q_{RF} is the quantity of diverted water that is reusable by other users. Q_{RF} naturally reenters the fresh water system.



* Effective portion of Return Flow that is made nonreusable due to degradation of quality.

Figure 1. Use categories (consumptive and nonconsumptive and beneficial and nonbeneficial) and fractions describing the disposition of irrigation diversions (after Clemmens et al., 1995 and Allen et al., 1996, 1997).

Impact of the Location within a Basin

Willardson and Allen (1998) recommended the splitting of a river basin into three regions (high, mid and low) to assist in assessing impacts of low "efficiencies" (i.e, consumed fractions) on downstream and other users. In general, the need for conservation programs and impact of such programs increases as one moves downstream (toward the ocean). In low regions of basins, the NRF (nonrecoverable fraction) of diverted water generally increases due to proximity to saline systems.

Nonreusable quantities of water arise in other uses of the water resource besides irrigation. For example, water allocated to "wild rivers" in northern California is in general not recovered for other uses and runs directly into the ocean and becomes nonrecoverable. Such water has a very low evaporated fraction (EF) but has a very large nonreusable fraction (NRF) and consequently, a large CF. Such uses of water should be described in the same terms as for irrigation so that the public understands the impact on total available fresh water in terms consistent with the descriptions used for other uses. A low CF for a city high in a watershed permits a large fraction of the returning water to be reused downstream after natural bioremediation and/or water treatment. A high CF for a large coastal city will result if nearly all of the sewage effluent (reusable under some circumstances) becomes nonreusable when it is discharged directly into the ocean. It does have high benefit, however, if injected to groundwater to reduce seawater intrusion. In some situations, it is "good" to have a "low" CF, since this means that much of the diverted water returns as a fresh water resource for subsequent reuse. However, because a low CF is equivalent to a low "efficiency", the latter term gives a falsely negative impression to the public, in the absence of rational fractional analysis.

Effect of Scale

Fractions can be calculated for any scale of interest. In the case of irrigation, this is typically at the field, subproject, project or basin scale. Generally, the nonreusable or Q_{NR} quantities of water for fields or conveyance systems in upper regions of irrigation projects are small relative to Q_{Div} and Q_{EP}, especially if hydrology and elevation promote convenient and timely reuse of water or return of water to the stream or to a recoverable ground-water system.

An example of this is the Little Willow Irrigation District in southwest Idaho (Allen and Brockway, 1983) where the geology and topography of the long, narrow mountain valley containing the irrigation project promotes rapid reentry and reuse of surface and subsurface return flows within the project boundaries. Irrigation "efficiencies" (or more correctly, stored fractions) of individual farms average only 0.30, but the total project irrigation "efficiency" or consumed fraction is 0.60 due to the reuse of water. The remaining 40% of diversions not consumed by the Little Willow project (i.e., 1 - CF) return to the surface water resource below the irrigation project and are diverted by other downstream water users, making the RF for the basin very high.

The acceptable magnitude for NRF for an individual lawn or field or other use may be different from the system-wide average NRF. Actual NRF may be low for fields or conveyance systems in upper regions of irrigation projects where the opportunity for reentry and reuse of deep percolation, surface runoff, spills and seepage is high. NRF may be high for similarly irrigated fields or conveyance systems near the lower portions of irrigation projects when percolation or runoff directly enters the ocean or brackish water bodies.

Fundamental Questions

There are fundamental questions that one should ask when evaluating the potential impacts of a “water conservation program” on ultimate water savings and impact. These questions are posed from a hydrologic perspective and adherence to the law of conservation of mass.

1. Where does the delivered water come from? (i.e., is it from a stream, ground-water, or lake?) Where is the location of the abstraction?

2. At what time of the year are the abstractions made? (i.e., what does the abstraction "hydrograph" look like?)

3. Where does the nonevaporated component of any applied water go? At what times? (i.e., hydrograph of flows of nonevaporated components)

4. Where does the nonevaporated water reappear as part of a ground-water or surface water system? At what times? In what quantities? With what quality?

5. What happens in the mean time (between the abstraction and the return to the resource)? What are the consequences of this time lag or spatial lag? (i.e., is there local stream dewatering? Are there junior appropriators without water?)

Reasons for Action

1. If there are local instream flow needs that are not being met, then reduce diversions with conservation. However, the conservation program will not create new water for other users outside of the specific system or enterprise. In fact, the conservation program may be an "ET sustenance" program at the expense of downstream users and may reduce downstream flows.

2. If the water use near a saline system (ocean, brackish sink, etc) so that nonevaporated components are impaired or lost via quality change, then a conservation program will have a good hydrologic impact

3. If there are system capacity constraints or if there is large invested treatment (culinary) or energy costs involved, then a conservation program should be considered for local economic reasons and may not result in savings to the water resource

Basic Conservation questions

1. How much of the water abstraction gets consumed or moves beyond local control? (What is the CF?)
2. Who benefits from "wasted" water when it reappears and is recovered?
3. Are current "downstream" users better off by any higher efficiencies created in systems upgradient by a water conservation program? Are the downstream users benefited quality wise?
4. Is other water available by other means?
5. Will conservation make "new" water available to other local or within-system consumptive processes so that the net effect of the conservation is even less water downstream? (this is in the opposite direction intended or purported by many conservation programs, but may be the hydrologic reality).

Conclusions and Recommendations

Irrigation is no longer an endeavor isolated from other users of the fresh water resource. For regional water management, determination of the consumed fraction and reusable fraction is much more relevant than irrigation efficiency, and the use of these fractions may help to eliminate misunderstandings. Emphasizing or promoting conservation program components that increase efficiencies, without strong caution and guidance concerning when and where water can be saved, may harm both users and the economy. Irrigation enterprises contemplating conservation investments must know whether environmental, economic or landscape health and crop yield benefits stemming from a local conservation program are worth the cost. The public and other groups that are interested in freeing up water supplies for new uses must know whether a conservation program will ultimately create new water.

The quantity impact of a given use should be expressed in terms of (a) the fraction of water it directly consumes, (b) the fraction, by virtue of that use, that is rendered unavailable to other users, and (c) the fraction that is returned to the hydrologic system for reuse. It is understood that the hydrology of irrigation projects and their impact on basin-scale hydrology can be complex due to the wide ranges and variations in geology, mineralogy and timing of ground-water flow systems. Therefore, the quantification of Q_{NR} and Q_{RF} may be difficult in some situations. However, the use of simple fractions serves as a good starting point for assembling a clear understanding and definition of the hydrologic destiny of fresh water diversions.

Conservation programs should target reduction of the product ($CF \bullet Q_{Div}$), which requires either reducing Q_{ET} (and thereby potentially reducing crop yields) or reducing Q_{NR}. In reality, many conservation programs target increasing the "irrigation efficiency" (IE), which may be counterproductive, since, as shown in Fig. 1, $IE \bullet Q_{Div}$ contains different terms than are present in $CF \bullet Q_{Div}$. As generally defined (Clemmens et al., 1995), $IE \bullet Q_{Div}$ includes some Q_{RF} and omits some Q_{NR}.

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