Technical concepts related to conservation of irrigation and rain water in agricultural systems

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Abstract

Forty percent of freshwater withdrawals in the U.S. are for irrigated agriculture, which contribute more than $50 billion to the economy. Increasing diversions of water for urban, environmental, and other uses will likely decrease water available to agriculture. Water conservation in agriculture is touted as a good method for minimizing the impact of reduced agricultural diversions on production. Because "wasted" water is often reused until it reaches the ocean, there are limitations to the true water savings that result from programs that aim to increase irrigation efficiency. True water savings can come from four areas: reduction of unnecessary evaporation and transpiration, more effective use of rainfall, reduction of deep percolation water that becomes severely degraded in quality, and reduction of runoff from fields that is not reusable downstream. Any other reduction in net water consumption must come from reductions in evapotranspiration from the crops grown, which requires either reduction in acreage or reduction in crop yield brought on by intentional plant water stress. Other benefits of field or district—

level water conservation may include increased in-stream flows (due to lower diversions) and energy conservation due to less pumping or more hydroelectric production – but not result in true water savings. Understanding the hydrologic settings is critical to determining true water savings from conservation practices. On-farm water conservation practices that provide true water savings at one location may be ineffective at another. In large irrigation projects, water delivery limitations often present obstacles to on-farm water conservation efforts.

Context of Irrigated Agriculture

According to the USGS (Hutson et al. 2004), roughly 189 million ML (1000 m^3 or 153 million ac ft) of freshwater were withdrawn for irrigation in the U.S. during 2000. This represents 40% of all freshwater withdrawals, or 65% excluding withdrawals for thermoelectric power. Surface water and groundwater represented 58 and 42%, respectively, of the total irrigation withdrawals.

USGS estimates that roughly 25 million ha (62 million ac) were irrigated during 2000. They also estimate that during 2000, the irrigated areas for surface, sprinkler and micro-irrigation were 12 million (48%), 11 million (46%), and 1.7 million (7%) ha, respectively.

The 2002 Census of Agriculture (NASS 2002) shows total harvested crop land in the United States at 123 million ha (303 million ac). Irrigated land during 2002 was 22 million ha (55 million ac), with roughly 20 million as harvested crop land and 11 million ha (27 million ac) from farms with all harvested crop land irrigated (fully irrigated farms). (These years do not match up with the USGS estimates and the land areas do not match because they reflect different estimation methods.) Thus in 2002, irrigated land represented 17% of the harvested crop land, while fully irrigated farms represent 9%. The market value of crops sold from harvested crop land was $95 billion in 2002. The market value of harvested crops from fully irrigated farms was $38 billion. Because of the difficulty in separating production on partially irrigated farms, NASS does not provide estimates for the total market values for crops harvested from all irrigated land. Based on what data are provided, we estimate the market value to be slightly over $50 billion. This does not include other production on irrigated land, e.g. pasture. Thus irrigated crop land

produced roughly 53% of the market value of crops harvested on 17% of the harvested crop land, while fully irrigated farms produced roughly 40% of the value on 9% of the land. This increased value is both the result of improved crop yield and quality, and the tendency to use irrigation on higher value crops.

The market value of products resulting from irrigation withdrawals is on average $290 per ML ($55 billion divided by 189 million), or $360 per ac-ft. This number is somewhat inflated because crops grown with only one or two irrigations during the season are counted even if most of the production resulted from rainfall only. (Individual values can be an order of magnitude higher or lower). Water is only one of many inputs to crop production. By comparison, water prices for agriculture range from less than $5 to more than $100 per ML. The cost of new water sources for some western cites are approaching $200 per ML, but are typically still less than the average market value of agricultural output resulting from the water.

The 2002 Census of Agriculture reports the following for irrigated crops in million ha: Hay and pasture 12.9, Grains 8.9, Cotton/sugarbeet/tobacco 4.3, Oilseeds (including soybeans) 2.5, Orchards 1.8, Vegetables 1.0, Potatoes 0.4, and other 0.3. The total cropped area is more than the total irrigated land area because of double cropping (i.e., 32 versus 22 million ha). The land area of a crop is almost inversely related to the market value per acre. Unfortunately, the census is not broken down so that this could be readily determined, but generally one expects pasture and grains to be on the low end of market value per land area and vegetables at the high end, with cotton and orchards in the middle. This also relates to the type of irrigation system utilized. Farmers growing low market value crops generally can not afford high cost irrigation systems.

Thus a large amount of the low-value crops are grown with surface irrigation or center pivots, since in some cases either can be the least expensive to own and operate, while higher value crops can afford the cost for the quality improvement of other types of pressurized irrigation systems, particularly perennial crops like orchards. There are exceptions, for example, in some locations lettuce is extensively grown under surface irrigation, while in other locations, pastures are irrigated with sprinklers. And some farmers may be unwilling to invest in improved irrigation systems, even though on paper it may appear to be in their best interest.

From the grower's perspective, the choice of irrigation method can be quite complex. Just a few considerations are listed below:

- The decreasing availability and quality of agriculture labor can quickly move a grower towards less labor-intensive irrigation methods. Some of the pressurized irrigation methods such as center pivots require very little labor and are also relatively simple to operate and manipulate. However, many soils, crops, and field sizes are not suitable for center pivots.
- On newly developed land, pressurized irrigation methods may be considerably less expensive than surface irrigation because surface irrigation may require extensive land grading.
- Drip or microspray irrigation may be popular on some crops, yet in some regions better yields and economics have been obtained with surface irrigation techniques. For example, in the Reedley/Dinuba area of central California, there was a large scale conversion to drip and microspray on stone fruit (peaches, nectarines, plums) approximately 20 years ago. Most of those orchards have reverted back to furrow irrigation. Central Arizona also saw large shifts to microirrigation on cotton 20+ years ago. Nearly all of that land has reverted to surface

irrigation because the expected yield increases used to justify the added irrigation-system cost did not materialize.

- If there is an extreme shortage of water, in practice pressurized irrigation methods can generally apply the limited water more effectively over the field than can be done with surface irrigation.

The issue addressed by the authors in this paper is somewhat simplistic – it deals with expectations of water conservation and yield increases when a farmer shifts from one irrigation method to another, or makes substantial improvements to the existing irrigation system. This paper attempts to blend considerations that are important to the farmer as well as society – which are usually different, and which reflect different financial sources for proposed improvements.

It is well established that crop production and water management are linked. Like other inputs, water is used as a tool to achieve more production. One cannot examine the impact of technology changes on water use without simultaneously looking at the impact on production. Unless their water supply is extremely limited, few growers will adopt new irrigation technology unless it either increases production or increases profit, for example by lowering costs for the same production.

There is no doubt that in many cases a shift from one irrigation method to another can result in an improvement in yield. Peppers seem to be a special crop that almost universally responds well to microirrigation, for example. Almonds provide excellent yields with double line drip or microsprayers (but generally require a higher evapotranspiration than under traditional surface

irrigation methods, likely due to increased irrigation frequency). However, the stone fruit example above indicates that things are not always so simple. Unpublished research by Burt on several hundred processing tomato fields in California showed that furrow irrigated fields had the same yields as drip irrigated fields. This may not be a fair comparison, since the poorest yielding fields were likely converted first. But the point is that there was no automatic dramatic, average increase in processing tomato yields when a shift in irrigation methods was made.

From a societal perspective, we should be looking at water productivity – the amount of product (yield or economic value) per unit of water consumed or otherwise not available for reuse (Clemmens and Molden 2007). And here it appears that pressurized irrigation methods inherently have a substantial advantage. For example, the nature of surface irrigation is that it occurs occasionally (once per week or two weeks). With surface irrigation, the top of the root zone dries out to the point that the nutrients (ammonium, phosphorus) that are predominately held in the upper soil are less available to the plant than they would be with more frequent pressurized irrigation (Burt 2006). Granted, the sophistication of fertigation in the US is decidedly low at the moment – but the potential for improvement with pressurized irrigation is much greater than with surface irrigation.

Webster's Dictionary defines consumption as "the utilization of economic goods in the satisfaction of wants or in the process of production resulting chiefly in their destruction, deterioration, or transformation." In this paper, water consumption is defined in terms of 'destruction and transformation' of the liquid resource as the conversion of liquid water to vapor by the process of ET, sometimes called consumptive use, and in terms of 'deterioration' as any

additional loss of water to an economically or physically unrecoverable location or state such as flows to the ocean or other saline sink. All other dispositions of water are considered to be nonconsumptive and reuseable in some form at a later time and perhaps at a different (downstream) location.

A noble objective is to identify practices for a geographic area that both improve farm profitability while simultaneously improving water productivity. The practices should also reduce negative impacts on power consumption, water quality, in-stream flow quantities, and air quality. Achieving these objectives requires a good understanding of irrigation practices, the hydrologic setting, and their interactions. The purpose of this article is to discuss the potential for improved irrigation and crop-production technology to improve both farm profitability and water productivity. The article is one of a series of papers based on a symposium held at the American Academy for the Advancement of Science Annual Meeting held in San Francisco, CA, February 16, 2007. Huffaker (2007) deals with the economic considerations and policy issue associated with water conservation programs. Evans and Sadler (2007) discuss crop-water productivity issues and the potential for precision agriculture and deficit irrigation. Letey (2007) discusses salinity issues and leaching requirements. Bennett et al (2007) discusses possible improvements in water use efficiency from plant genetics. Saseendran et al (2007) provide an example on the use of models to evaluate options for improving water use efficiency.

Molden (2007) provides a comprehensive view of international water management issues. Cai and Rosegrant (2004), among others, provide a case study in examining the trade-offs in

competition among water uses. Herein, we limit the discussion to more technical issues regarding irrigation system performance

Water Balance and Water Conservation

Numerous government-funded projects have had the expressed objective of conserving water. Quite typically, these projects focus on on-farm irrigation scheduling or on-farm irrigation system improvements. In general, these investments have helped the farmers. But the water conservation objectives have not always been met (Huffaker 2007).

Generally, 'conservation' programs have the aim of reducing current diversion rates or volumes by a specific use with the intention of producing 'new' water for new diversions by the same use or by other uses. On a basin or global scale, conservation should have the objective of reducing the consumptive component (Allen et al. 1996 and Burt et al 1997). Even locally, if the consumptive component is not reduced by conservation, then no new water may be freed up by 'conservation efforts.' For example, reductions in 'leakage' and seepage from an irrigation system that ultimately reappear as return flows to the stream at some point in space and time may reduce local diversions and leave water in the stream. This outcome may be good locally, but the return flows may reduce by the same amount as reductions in diversion, and thus, hydrologically, at some point downstream, no net change in stream flows may occur. Thus, there is little advantage from the conservation program as the scale of assessment increases.

For any type of water conservation program, it is important to understand (i) what the objective is, and (ii) what happens to the applied irrigation water, i.e., where does all the water ultimately go? To reduce water consumption (again, defined as water with a destination of evapotranspiration or a non-usable degradation in quality), it is often insufficient to improve the "apparent" application efficiency (measured by a variety of indicators) because of the influence of hydrology and geology within a river basin on recycling and reentry of diverted water into some part of the surface water system. There is no single efficiency term that is useful in all contexts and for all purposes. If one understands what happens to all components of the diverted water, then one can assess what benefits result from water conservation.

A good example from the urban sector is low-flush toilets. They are definitely beneficial for reducing costs (chemical, power) for water treatment and for metering scarce water during droughts. But in non-coastal cities, low-flush toilets may be of little benefit to the total fresh water resource. Take for example a city on the shore of the upper Mississippi River. Water is withdrawn from the river, treated for municipal use, and distributed to users. Following each toilet flush, the waste water enters sewers and goes to a wastewater treatment plant, where it is treated and discharged back to the river. A low-flush toilet reduces the amount of water diverted from the river, and may reduce the cost of water and wastewater treatment, but nearly all of the diverted water returns to the river to rejoin the water not diverted, and although perhaps degraded in quality, is generally reusable at locations downstream. There is very little if any water conservation benefit to the river in terms of producing new quantities of divertible water.

In contrast, many coastal cities discharge their wastewater into the ocean. Here, essentially all diverted fresh water is consumed and consequently a low-flush toilet will reduce the amount of fresh water discharged to the ocean – a real water conservation benefit. This illustrates the importance of following the water as it is manipulated by man and within the greater hydrologic system.

The same situations occur in irrigated agriculture. Efficiencies are often defined to determine the required size of a water supply and irrigation system. They do not necessarily infer an unrecoverable loss of useable water to the fresh water system. In high-mountain meadows, nearly all unused irrigation water is returned to the hydrologic system and ends up as stream flow. Here improving field efficiency has little to do with reducing basin water losses, but has more to do with improving production and reducing costs and, in some cases, may improve the timing of stream discharge for the area or improve stream flows immediately downstream from the diversion (upstream from return flow entry or prior to entry of return flows) or improve water quality in the stream downstream by reducing low quality return flows. In reality only the consumed water is lost (converted to water vapor) when high in a basin, since essentially all unconsumed water flows downstream for reuse.. Whether conserved water remains in the stream depends on water rights and who has a legal right to the stream flow. Often, water rights law allows the taking of conserved water by third parties who have senior, unfulfilled rights. In lower portions of river basins, particularly those near the ocean or a saline sink, or overlying saline groundwater, unused irrigation water is often not recovered and is lost for future fresh-water use due to its mixture with saline water. Here, improvements in irrigation efficiency have a direct benefit. But even here, there can be arguments about non-agricultural environmental

benefits related to “wasted” return flows, which often create wildlife habitats by providing relatively freshwater inflows to saline water bodies (Allen et al 1996). In coastal areas, percolation of fresh water can be useful in reducing sea water intrusion into fresh ground-water systems.

From a simple water conservation standpoint, things are not always so black and white as reducing flows to a salt sink. Some unused water is relatively easily recoverable, some unused water is degraded in quality but still usable, some unused water recharges groundwater, but may not be reusable for years while in transit or storage underground.

Burt et al. (1997) suggested a systematic way to categorize the water that is diverted for irrigation. In evaluating the performance of irrigation systems, one has to be careful to establish appropriate physical boundaries and time frames, since water is often in transit or in temporary storage. One can only evaluate the performance of an irrigated area by examining the irrigation water when it leaves the defined boundaries of interest. The applied irrigation water can be placed into several categories:

1. Water consumed by the crop within the area for beneficial purposes.
2. Water consumed within the area under consideration but not beneficially.
3. Water that leaves the boundaries of the area under consideration but is recovered and reused.
4. Water that leaves the boundaries of the area under consideration but is either not recoverable or not reusable.
5. Water that is in storage within the boundaries.

These categories are shown visually in Figure 1. This categorization can help to identify improvements that would result in true water conservation. The following five points expand on and explain the five categories above:

1. **Water consumed by the crop within the area for beneficial purposes.** Here, the water is used to produce a crop and is consumed by transpiration from stomates of leaves or by evaporation from plant surfaces or from soil beneath and between plants. Following rainfall or irrigation, the cooling effect from evaporation reduces plant transpiration (Burt et al. 2005). At full crop cover, the net effect of evaporation is a slight increase in the combined evapotranspiration (*ET*), with larger increases during early growth stages. That evapotranspiration which would equal the transpiration from a non-stressed crop with a dry soil surface is referred to as basal *ET*. Reducing transpiration generally reduces yields or marketable products. Reducing evaporation, particularly that part which offsets transpiration, may or may not influence yield, depending on the crop and environment. All of the basal *ET* is considered as beneficial for plant production.

   One option to reduce water consumption is to fallow land or take it out of production. This results in real water conservation, particularly in arid environments, since *ET* is substantially reduced. However, fallowing land can have negative environmental (soil salinization, wind erosion, etc.) and regional economic consequences (third party impacts on equipment suppliers, agronomic suppliers, local taxes, etc.), if not done properly (McBean and Bautista 1995, Wallender et al 2002). Genetic improvements to produce more crop with less water are possible in some cases, but usually it's in the form of more crop with the same water (or the same gross production on less acreage and thus less

water). This limitation occurs because crop biomass accumulation is through photosynthesis where carbon dioxide enters the plant through the same stomates as water vapor exits. Therefore, the ratio of yield to transpiration in a specific climate is limited by the physiology of the crop variety. (Harvestable yield is also influenced by other factors not discussed here).

Given full vegetation cover, transpiration is generally governed by atmospheric conditions (air temperature, air humidity, wind speed and solar radiation) and is relatively consistent among crop types. This is evidenced by consistency among maximum ET (crop) coefficients for agricultural crops, which nearly all peak at the same value under full ground cover (Doorenbos and Pruitt, 1977, Snyder et al., 1989, Wright, 1982, Allen et al., 1998). This suggests that climate will dictate transpiration rates per unit of land under full vegetation cover if water is fully available. From this, one might note that low yields do not imply low evapotranspiration. Evapotranspiration tends to be close to potential regardless of yield, except under extreme water stress conditions.

2. **Water consumed within the area under consideration but not beneficially.**

   Evaporation from soil and plant surfaces varies from a few percent of total consumption to more than 40%, depending on a variety of factors (Burt et al. 2005). The evaporation in excess of the basal *ET* for an efficient irrigation system is typically on the order of 5% to 10%. Much of this is unavoidable (Burt et al 2005). Buried drip irrigation claims a benefit here, since the soil surface is sometimes not wetted and thus the evaporation component can be reduced with only slight increase in transpiration. However, claims of large savings in water consumption are physically unreasonable, since buried drip systems can generally only reduce evaporation by about one-half, due to unavoidable

upward fluxes to the soil surface and due to wetting by precipitation, and consequently can create savings of only 5 to 10% of total consumptions and likely only 2 to 5% of total water diverted. Similarly sprinkler irrigation often claims a benefit for improving efficiency, however in some settings, the extra evaporation caused by frequent irrigation and spray evaporation may result in more net consumption than field runoff losses from other irrigation systems that are recoverable. Many fields have non-cropped areas that are used for turn rows, furrows, border dikes, etc. Additional soil evaporation results if these areas are wetted during irrigation. Irrigation systems that do not wet these areas can reduce water consumption. Savings might be on the order of a few percent.

This category also includes water that is lost through evapotranspiration from weeds, trees, phreatophytes, etc.. Many of these losses are difficult or costly to avoid, but there are opportunities in some cases. Some of the lost water may have environmental benefits by supporting trees, windbreaks, incidental wetlands, etc. that are attractive to and supportive of wildlife. However, it also includes *ET* from cropped areas of the field that are not productive. There can be areas that are waterlogged, have high soil salinity, have low soil fertility, have insect or disease damage, etc. that have significant *ET* but with little useful production. This non-producing *ET* within the cropped areas is not considered when determining traditional irrigation or application efficiencies. (Any crop *ET* within the field is assumed to be beneficial). In well managed fields, this component is small. But it can be significant in some situations.

3. **Water that leaves the boundaries of the area under consideration but is recovered and reused.** Water that is not degraded and is recovered and reused at some later point in time and/or at some lower location in a stream or ground-water system is not a target

for water conservation. The water is, in all likelihood, already being reused, so reducing the amount of this water entering the irrigation system often has little real benefit. There are exceptions, for example where reducing diversions reduces cost of delivering water and collecting runoff, or improves the quality of this water, or where leaving the water in a reach of a stream has a local environmental benefit. In some cases, the delay in unconsumed irrigation water returning to the stream has an environmental benefit by buffering stream flow during low-flow periods or by reducing stream water temperature through groundwater recharge. Water lost to deep percolation that recharges groundwater during high water supply years may effectively store water for use during supply deficiencies.

4. **Water that leaves the boundaries of the area under consideration but is either not recoverable or not reusable.** This unrecoverable water should be the primary focus for water conservation efforts. Here nonevaporated water is unrecoverable because of large depths to groundwater (for water that enters ground-water systems) or is not reusable because of salinization or entry into a saline body, including the ocean. This component can also include some of the uncontrolled runoff that is difficult and inefficient to use by downstream farmers. A reduction in water applied for irrigation that would become unrecoverable means that conserving it can free it up to be used for other purposes. It is truly water saved. However, there are cases where this water that is unrecoverable for diversion provides environmental benefits. Even though it can no longer be considered fresh water, it may be fresher (less saline) than sea water and provide some benefit to coastal and marine ecosystems.

5. **Water that is in storage within the boundaries**. Irrigation water that is in storage within the area of consideration is not considered as used. Its ultimate fate is yet to be determined. The delay caused by storage may have positive or negative economic and hydrologic impacts.

Often overlooked in the discussion of irrigation system performance is the contribution of rainfall, and its effective use. Rainfall contributions to crop *ET* vary from less than 10% in the desert southwest to more than 90% for wet years in areas of supplemental irrigation. In areas of dry-land production (where typical rainfall does not meet crop *ET* requirements) and where supplemental irrigation is practiced, the effective use of rainfall is extremely important. Specific practices are used to collect and store rainwater. These practices include reduced tillage, irrigating every-other-furrow, vegetative mulches and soil surface shaping (e.g., furrow diker-dammers) to reduce runoff (from rainfall and irrigation) and to reduce soil evaporation. These can be extremely effective water conservation practices (See Howell et al. 2002). Such practices are not often used in areas with little in-season rainfall. Again, the potential for improving the effective use of precipitation is site specific, and may actually decrease the availability of water downstream, if excess precipitation recharges groundwater or contributes to river flows.

Irrigation Efficiency and Consumptive Use

Burt et al. (1997) define irrigation efficiency (*IE*) based on the water-balance partitioning discussed above, namely

$$IE = \frac{Volume\,of\;irrigation\;water\,benefically\,used}{Volume\,of\;irrigation\,water\,applied - change\,in\,irrigation\;water\,storage} x100\% \qquad (1)$$

The denominator represents all applied irrigation water that, over a specific time period, leaves the boundaries, while the numerator includes the water that leaves while providing some benefit. There is a definite time component associated with *IE* and with Eq. (1). Other beneficial uses, in addition to crop *ET*, include water used for leaching salts, frost control, crop moisture control, etc. *IE* is applied to a system with well defined boundaries and for a specific time duration, e.g. a crop season, annual, etc. It does not apply to an irrigation event (discussed later).

Burt et al. (1997), Willardson et al. (1994), Allen et al. (1996) and Molden et al (2001) argue that the irrigation efficiency term is not appropriate to use when examining an irrigated area from a hydrologic perspective because low values can imply overly negative stewardship of water diversions. They argue instead for use of terms similar to Irrigation Consumptive Use Coefficient (*ICUC*) or 'consumed or depleted fraction.' The *ICUC* is defined (Burt et al. 1997) as

$$ICUC = \frac{Volume\,of\;irrigation\;water\,consumptively\,used}{Volume\,of\;irrigation\,water\,applied - change\,in\,irrigation\;water\,storage} x100\% \qquad (2)$$

The *ICUC* includes all water consumed, whether beneficial or not, and does not include unconsumed water that is beneficial.

Application Efficiency and Irrigation Uniformity

No irrigation systems can apply water with perfect uniformity. Nonuniformity influences yields and irrigation efficiency. Figure 2 shows a typical distribution of infiltrated water resulting from

irrigation, where infiltrated water depths are sorted in increasing order. If the net amount of water applied during an irrigation (amount applied less runoff) is the same as that required (e.g., to fill the soil water deficit), then, because the distribution of water is never perfect, half of the field will receive too much water while the other half not enough.

The normal response of a farmer to this distribution of water is to apply more water so that a larger fraction of the field has an adequate amount. In Figure 2, with a coefficient of variation (*CV*) for depth of infiltrated water within a field of 0.2 (20%), one would have to add 134% of the required amount in the field to provide the required amount (100 in these graphs) to the quarter of the field area that receives the least water. The coefficient of variation is the standard deviation divided by the mean. We would have to add roughly 170% of the required amount to provide 98% of the field with adequate water for full ET. Because of the tradeoff in extra water versus the amount in deficit, as well as other practical considerations, satisfying the average of the low quarter of the field has been a practical guideline in the U.S. for half a century. An alternative to adding extra water is to improve the uniformity of water application. By reducing the coefficient of variation from 0.2 to 0.1, less water has to be applied to satisfy the low-quarter criteria, where only 15% extra water would be needed, as opposed to 34%, to meet the water requirement of the low quarter (Figure 3). An added benefit when the uniformity is improved is that the amount of deficit in the area under irrigated is less and the potential for water logging and salinization is reduced.

Burt et al. (1997) define application efficiency (*AE*) for an individual irrigation event in terms of the ability of the irrigation system to apply a specified target depth of application, namely

$$AE = \frac{\text{Average depth of irrigation water contributing to the target}}{\text{Average depth of irrigation water applied}} x100\% \quad (3)$$

Unlike irrigation efficiency where water in storage is not included as an input, the intent of an irrigation event is to put water into soil water storage for later use. *AE* considers the water that goes into soil water storage as well as other possible reasons for irrigating, for example leaching. Most evaluations and designs for irrigation systems consider *AE* and imply that this represents *IE*.

Most water conservation programs geared toward improving irrigation and/or application efficiency have resulted in irrigation systems that provide better distribution uniformity. This translates to less deep percolation and less of the crop under deficit. Both of these are considered to be positive benefits by farmers and provide motivation to undertake conservation programs (in addition to any cost sharing on irrigation systems). The reduced deep percolation is generally the motivation for the conservation advocate. The general results of such improvements are more yield, but also more water consumption (i.e., *ET*) via reduced areas of soil water deficit, both resulting from the improvement in uniformity. In areas where excess infiltration results in water logging, improving uniformity should improve yields, but may not increase water consumption since water logged areas may consume as much or more water, due to capillary flow to the soil surface, than a cropped area (i.e., non-beneficial evapotranspriration). If deep percolation and runoff waters are captured and reused downstream, then improvements in field irrigation efficiency may result in no net gain in water available on a watershed basis, and may actually reduce water available downstream. The availability and usefulness of return flow frequently depends on the lag time of the return flows. Where good quality groundwater is pumped from an unconfined system, conservation efforts seldom provide new water.

Water conservation efforts

Water conservation efforts in irrigated agriculture are usually focused on:

- Improving the infrastructure of the irrigation system so that water can be controlled more easily and applied more uniformly.
- Improving the management of the irrigation system so that the right amount of water is applied at the right time.

Water conservation programs that improve the irrigation infrastructure are the most straightforward to implement. It is relatively easy to document improvements in the application efficiency of irrigation events, although this may not translate well to seasonal irrigation efficiency and generally does not translate to *ICUC* improvements at the watershed or river basin scale. Generally there are two areas where application efficiency can be improved: 1) reducing the amount of water that runs off the field and 2) reducing the amount of water that percolates below the root zone, often called deep percolation. The first is relatively easy to observe, measure, and improve. This water can also be collected and reused. The deep percolation water is difficult to observe or measure. It typically results from a nonuniform distribution of infiltrated water, intentional leaching of salts, or simply applying too much water. Again, these efforts can increase *AE*, reduce irrigation diversions and reduce water 'use,' but they may often not reduce water consumption (conversion of liquid water to vapor) and thus may not create 'new' water.

Water conservation efforts that focus on water management are geared toward determining when to irrigate and how much water to add. Timing of irrigation is generally geared toward avoiding plant stress. However, there is often significant variability in soil properties such that even with uniform irrigation, plant stress may occur in some areas of the field before others. Thus again, there may be a balancing of allowing some areas to show small amounts of stress before irrigating, to reduce numbers of irrigations and total amount of water applied. Irrigating frequently can result in excess evaporation from wetted soil. All of this is complicated by nonuniform and uncertain rainfall contributions, uncertain and variable soil water storage capacity, uncertain and variable rooting depths, and uncertain and variable evapotranspiration demands. Documenting the improvements resulting from improved water management alone can be difficult, unless there has been gross over- or underirrigation.

The physical irrigation system may place lower limits on the amount of water that can be efficiently applied. Efficient irrigation scheduling and metering of water to the soil may suggest irrigating when the soil water deficit is, say, 30 mm when the irrigation system, because of its type or design, is only capable of applying a minimum of 60 mm with reasonable efficiency. Thus the physical and management improvements need to be integrated.

While most of the discussion here has focused on field irrigation systems, these concepts also have a parallel for the water delivery part of the system. Here conservation efforts are primarily on reducing canal seepage and spills and on supporting improved field irrigation systems by improvements in service. Again, any changes in water “lost” to the canal system have to viewed

from a hydrologic perspective. Is the water currently “lost” being recovered and used downstream? Or is it irrecoverably lost as a freshwater resource?

Salinity Issues

The above discussions about categories of water destination and what constitutes conserved water is clouded by water quality, in-stream flows, and the need for drainage.

As rainfall percolates through soil and rock, it dissolves salts. When water is used to irrigate plants, much of the water is evapotranspired and the salts that were imported with irrigation water are left behind in the soil. If salts are allowed to concentrate in soil, crop growth will be impaired. Additional water is needed to leach these salts from the soil to maintain a healthy soil environment for plant growth. In humid regions, there is typically sufficient rainfall to leach salts. In arid areas, leaching is typically provided by applying additional irrigation water that percolates through the soil. The amount of water needed and beneficially used for maintaining a salt balance is somewhat controversial. However, as the water salinity increases, the amount of water required for leaching also increases. Thus for a given crop, as the water salinity increases, more water needs to be diverted and infiltrated into the soil. In this regard, reducing water salinity can, in effect, conserve water.

A number of relationships have been developed for estimating the leaching requirement (*LR*), or the amount of water that is required to leach salts to acceptable levels (Ayers and Westcot 1985). One of the simplest equations for *LR* expressed as a fraction of infiltrated water, for illustrative purposes, is

$$LR = \frac{\mathrm{EC_w}}{[5\mathrm{EC_e} - EC_w]} \quad (4)$$

where EC_w is the electrical conductivity of the irrigation water and EC_e is the salinity of the saturated paste extract at which crop yield begins to be affected. For a given source water, the relationship between electrical conductivity and salt content is essentially linear within the typical range of interest here. If we started with an EC_w of 0.5 dS/m (about 340 ppm), for a relatively sensitive crop like alfalfa with EC_e of 2 dS/m, applying Equation 4 gives a LR = 0.053. This means that one would have to apply 1.056 [1/(1-*LR*)] times the required *ET* at the point in the field that receives the least amount of water. This would theoretically avoid crop yield declines from soil water salinity

The bottom line is that all of the salt that was imported in a relative depth of "1.056" units of water would now be concentrated into a relative depth of "0.056" of drainage water from the root zone – or in 5.3% of the applied water. Neglecting precipitation of the salts (which is inaccurate in the case of Colorado River water, but which nevertheless does not detract from the general argument), this means the deep percolation water at that point in the field is about 19 times more concentrated than the original irrigation water. Because of non-uniformity of field irrigation and imprecise irrigation timing, the ratio of concentration across the whole field is much less than 19 times.

Letey and Feng 2007 claim that Equation 4 greatly over estimates the leaching requirement, because it assumes uniform salinity conditions in the soil profile, while the lower soil layers can actually be much more saline. Ayars and Schoneman (2006) have demonstrated that with good water management, salt can effectively be stored in the soil below the root zone, such that less

salt in taken out in the drainage water than enters with the irrigation water. However, one must also consider the leaching effectiveness. In non-uniform and cracking soils, one may have to leach more water on average to provide sufficient leaching in less permeable zones of the soil.

Nevertheless, it is a fact that as water is used for irrigation within an arid river basin, the concentration of salt in the remaining water is progressively greater as one moves downstream. An example of this is the Colorado River system. The consumption of irrigation water results in an increase in river-water salinity caused simply by *concentration* effects. Such concentration effects are not influenced by irrigation efficiencies, per se, but more by loss of liquid water through *ET*. However, there is an additional loading (additional of salt mass) in some geologic environments as the deep percolation water that passes through the root zone removes salts from underlying soil and rock. An example of this is the Mancos shale formations of western Colorado and eastern Utah. Here, the more water that passes through the soil and rock, the more salt load is added to the river system. In such settings, water conservation efforts aimed at reducing deep percolation will result in less salt load added to the river, which in effect makes the remaining water "more valuable" because it is less saline. A smaller percentage of that water will be needed on downstream farms to leach out the salt imported with the river irrigation water. Reduction of on-farm irrigation applications in the upper basin in effect saves water when it is eventually used downstream.

Figure 4 shows the effects of changing the consumed fraction of diverted water from 60% to 75% in a basin where the salt is in balance (i.e., salt entering basin with irrigation water equals salt leaving basin with drainage water). For simplicity in this example, there is one unit of salt

per 10 units of water. Note that the consumed water (*ET*) carries no salt so that the incoming salt is concentrated in less outflowing water. (In this case, 2.5 times more concentrated). By improving the efficiency, less water and salt come in, the consumption is the same, less salt also flows out, but the exiting water is still much more concentrated (4.0 times more concentrated). The increase in consumed fraction (e.g., due to efficiency improvement) results in slightly less salt in the returning water, but only because less salt was diverted. For the river, the same amount of irrigation water is removed via consumption (*ET*), with no salt removal, so that the change in *IE* and *ICUC* makes no change in the condition in the river at points some distance downstream. Depending on other factors, the improvement in efficiency may or may not make more water available on a watershed basis. Keller and Keller (1995) recommended expressing the IE term as an 'effective efficiency' that accounted for effects of salt concentration on economic usefulness to downstream users. They essentially combined Eq. (1) with a *LR* term from Eq. (4).

In systems where the excess applied water leaches salt from soil and rock, the situation changes drastically. The more water that passes through the system, the more salt that is mined and returned to the river. Suppose in our example, 1 unit of salt is added per 2 units of deep percolation water. As shown in Figure 5, increasing the consumed fraction reduces the amount of salt returning, even though the concentration of salt in the water is slightly higher. In this case, improving efficiency has a substantial impact since it changes the mass of salt added to the downstream water supply. It should be noted that some large river basins, such as the Snake River basin of Wyoming, Idaho, Oregon and Washington, have low salt levels in the river, connected ground-water systems and geological strata, and are thus not plagued by the salt loading problem.

High Water Table and Drainage Issues

Soil drainage is required from most crops to provide root aeration. Excess soil water will cause crop stress and “scalding,” particularly at high temperatures. In arid areas, drainage is also used to remove excess salt that is applied with the irrigation water. Because fields are sloped, excess water applied at the high end of a field can percolate to groundwater and cause waterlogging at the low end of the field. The same conditions happen within a watershed. Excess water applied to fields high in the watershed can cause high water tables and drainage problems on fields that are low in the watershed. Lack of adequate drainage and/or excess water application can thus cause significant non-beneficial consumption of water. Waterlogged plants typically do not yield well, although the total evapotranspiration can remain high. Waterlogging contributes to weeds that are high water consumers. High water tables can also directly feed soil evaporation through the natural capillary rise from the water table. In addition, high water tables from irrigation also feed additional evapotranspiration from the areas that are not cropped; including fallow fields and un-farmed areas. This can be a significant component to an irrigation project water budget.

Drainage issues can occur in all hydrologic settings. For example in high mountain meadows, it is a common practice to just let water flow continuously through fields (low labor costs). This excess irrigation leads to water logging and low production. Because of low temperatures, the impacts of waterlogging are not as obvious as they would be at higher temperatures. Evapotranspiration may be only slightly higher than with good irrigation management, but production is very low, resulting in low water use efficiency. Managing crop production in arid

areas with shallow (close to the surface), saline water tables is a significant challenge (Burkhalter and Gates 2005). Here production losses are more obvious. Letey et al (2002) discuss the problems and issues related with removal of drainage water. Hanson and Ayars (2002) show how improved irrigation can reduce the drainage volume. Ayars and Schoneman (2002) demonstrate that water table control can be used to effectively control soil water and plant water uptake from both the root zone and shallow groundwater. Even so, the negative impact of waterlogging, soil salinization, and non-productive evapotranspiration from these areas remains a significant issue.

Case Studies

Efficiency Measurement. Rice et al. (2001) demonstrated some of the complexities of evaluating field irrigation systems and the implications for water conservation. In this study, a sloping furrow irrigated cotton field was monitored for four seasons (years). Irrigation inflow, runoff, and advance were measured each irrigation. Soil water was measured through the entire season to determine additions to soil water from irrigation and water consumption. The application efficiency was determined for each event and the irrigation efficiency was determined as a cumulative effect over time. Application efficiency (*AE*) was determined as the volume of soil water deficit at the time of irrigation divided by the volume applied (assuming 100% fulfillment of soil water deficit). Irrigation efficiency (*IE*) was calculated as the beneficial use (consumption by the crop) divided by the volume applied, accumulated from the start of the irrigation season, as described by Burt et al (1997).

Figure 6 shows the results from 1994. The actual seasonal irrigation efficiency was roughly 60%, whereas *AE* of some irrigation events was much lower. Clearly, evaluation of this field based on measurement of application efficiency for one irrigation event might give misleading results. Low application efficiencies during early irrigations such as the second irrigation when the crop roots were not very deep are common since the shallow root zone is dry and the irrigation systems cannot apply light amounts of water. Low application efficiencies late in the season can be caused by not adjusting the application depth for the soil water deficit, or irrigating too frequently. For this field, runoff was not recovered, so the easiest method to improve irrigation efficiency for the field was to recover and reuse the runoff. Attempts to reduce runoff, i.e. through irrigation of every other furrow, for this field contributed to more deep percolation and no real improvement in *IE*. Unrecovered runoff for this field resulted in soil evaporation and phreatophyte *ET* from borrow ditches. These evaporative fluxes constituted a loss to the river basin. Deep percolation may eventually reach deep groundwater, but some may be lost or degraded in the vadose zone. Here improvements in irrigation efficiency may likely represent true water savings, depending on the ultimate fate of unevaporated surface runoff and deep percolation. This example highlights the important differences between application and irrigation efficiency, and the complexity of measuring irrigation efficiency on an appropriate time scale (e.g., seasonal or annual).

Efficiency Improvement. From 1975 to 1986, the Soil Conservation Service (SCS, now Natural Resources Conservation Service or NRCS) implemented an improvement program in the Wellton-Mohawk Valley (Bathurst 1988) as part of the Bureau of Reclamation Colorado River

Salinity Control Program (Salinity Control Act, Public Law 93-320 and amendments). The Bureau of Reclamation purchased 1,840 ha which were taken out of production (USDI 2005). Improvements in irrigation systems were made on 19,278 ha out of the remaining 25,110 ha (77%). Cost sharing for many practices was 75%. Prior to the project, land was graded with conventional equipment and most surface irrigated fields had some slope. After the project, nearly all the land was converted to level basins (zero slope in all directions) with laser-controlled grading equipment. Prior to the use of laser-controlled grading equipment level basins tended to be bowl shaped so that water infiltration was greater toward field centers. Flow measurement flumes were added so that producers could read the canal flow rates delivered using wall gauges mounted on the canal. There is essentially no surface runoff from the level fields, so that all excess water percolates to saline groundwater. Total financial assistance was $18.8 million. The cost of technical assistance was roughly $4 million. (Such assistance is routinely provided to any land owner in the U.S.) Land owners provided $6.3 million in cost sharing, plus the cost of other improvements that they conducted on their own.

Table 1 summarizes the water use on three of the major crops before and after the project. Also shown is the basal *ET* for these crops, taken from Erie et al. (1982). Rainfall in the area is negligible (roughly 75-100 mm/yr) and is typically much less than soil evaporation, which is often considered beneficial due to cooling effects and reduction in transpiration demand (Clemmens and Hunsaker 1999). Thus the ratio of basal *ET* to water use (applied) gives a rough indication of *ICUC*. Based on individual field observations, *ICUC* increased from about 60% to about 80% as a result of the irrigation improvements.

Table 2 shows the changes in crop yield in the Wellton-Mohawk valley following the on-farm improvement program. Some of this yield increase is likely the result of better water management (e.g. irrigation scheduling) and may not be entirely due to the conversion to laser-graded level basins. A point of note is that the higher yields likely translated into higher transpiration and thus higher water consumption by the crop due to more uniform and consistently higher soil water availability throughout the fields.

Drainage water from this project is pumped from the aquifer because the groundwater under this section of the Gila River is blocked from flowing downriver by a large underground rock outcrop. The salinity of the drainage water is roughly 3700 ppm, and is unusable for irrigation of most crops. Prior to the project, the drainage water was pumped into the Gila River, which flowed back to the Colorado River and eventually into Mexico. This return flow was used as part of the obligation to supply Colorado River water to Mexico. Because the Mexicans complained about the poor quality water, a drainage canal was built to carry the drainage water to the Sea of Cortez. This improvement project was initiated to reduce the volume of drainage water.

Since 1964, the Bureau of Reclamation has compiled records on water diverted to the project and return flows (BoR 1964-2004). Since both diversions and return flows are measured, consumptive use can be calculated as the difference, assuming no long-term storage changes and that other inputs and outputs are minor. This is the basis for the official decree accounting of water use for projects along the Lower Colorado River. The *ICUC* determined from these records is shown in Figure 7. Flood flows in the Gila River in 1979, 1980, 1984, and 1985 essentially invalidated the decree-accounting water balance assumptions for those years. Smaller

flood flows occurred in 1973, 1981, 1984 and 1993, making water balance for those years questionable, as well. The Bureau of Reclamation also computed more detailed water balances for the years 1970 to 1990, based on measurement of flood inflows and outflows, rainfall, groundwater volumes, etc (BoR 1990). These results, also shown in Figure 7, are in agreement with the farm-based assessments of *ICUC* changing from roughly 0.6 to 0.8. After completion of the project however, there were significant changes in cropping patterns, with lettuce going from less than 2,000 ha to roughly 10,000 ha. This corresponded to a significant drop in *ICUC* due to more frequent irrigation and lower consumptive use requirements.

Table 3 shows the average volumes of water diverted, returned and consumed for pre-, during, and post-project conditions, excluding flood years. (1 km^3 = 0.81 million ac-ft). Diversions from pre- to post-conditions were reduced about 17%, with a 7% reduction in land area due to land taken permanently out of production. Return flow volumes were reduced 30%. Consumption was reduced only about 3%, even though land area reduced 7%. The program essentially “saved” or “conserved” 0.01 km^3 per year (82,000 ac-ft/yr) even though total diversions decreased by 17%.

Table 4 shows values for pre- and post-conditions expressed in terms of volume per unit area. Diversions were reduced about 10%, return flow reduced 30% and consumption went up just slightly. While the discussion here suggestes that such a change in consumption is to be expected based on the improvement irrigation uniformity and the reported yield increases, some changes in consumption may have been caused by changes in cropping pattern.

The resulting water conservation improvements reduced water diverted from the river, and since none of this drainage water returns to the river for downstream use, all of this non-diverted water is considered conserved. However, the saline drainage water is currently the only Colorado River water entering the Sea of Cortez. Even with the high salinity, it is still relatively fresh compared to sea water and is considered an environmental benefit. On the flip side, the water diverted to the Wellton-Mohawk Project is part of Arizona's share of the Colorado River. More recent changes in cropping patterns (e.g., more irrigation of lettuce) have reduced *ICUC* and increased the drainage flows. Since the drainage canal was built, Arizona no longer receives credit for this return flow. They would like to reclaim and recapture this water to augment their current supply. The current U.S. obligation to Mexico is supplied through the Colorado River itself, and all of this water is diverted for irrigation use within Mexico. This example demonstrates some of the political complexities associated with assessing the utility of water conservation programs.

Recovering Seepage Losses. San Diego Water Authority is paying for a massive canal lining project of the All-American Canal that conveys water from the Colorado River toward the large US irrigated areas of Imperial and Coachella Valleys. The large canal runs parallel to the California-Mexico border. Appreciable seepage (0.12 km^3/yr Styles 1993) from the canal is lost to the US – but it does provide a groundwater supply to regions of the Mexicali Valley in Mexico. For the US water users, the lining project is a reasonable, excellent example of water conservation – they are in dire need of more water and they will eliminate non-beneficial conveyance losses. However, if the water balance spatial boundaries for consideration of irrigation efficiency were extended to include the Mexicali Valley, the canal losses would not be considered as losses at all – they are staying within the water balance boundaries and are

ultimately put to ‘beneficial’ use (in Mexico). As so often happens, the water balance is much more complicated than was understood years ago when various agreements and water rights were established.

In the 1920s, the Roosevelt Water Conservation District was formed east of the Salt River Project (SRP) in central Arizona to provide water savings by lining SRP canals. This predated significant groundwater pumping and all land was served from surface waters. The canal seepage recharged groundwater and, in fact, in the 1950s, the Roosevelt Irrigation District was formed southwest of SRP to help alleviate high water tables and drainage problems near the confluence of the Gila and Salt Rivers by pumping water from the deep alluvial aquifers to irrigate additional land. At the same time, SRP and others began significant groundwater pumping to augment surface supplies. In 1980, the State of Arizona passed a groundwater management act because of significant over pumping in major river valleys, including the Salt River. Once groundwater pumping began, it would have been hard to justify developing irrigation land through RWCD based on conservation effects, since the “losses” from the canal entered ground-water systems that were now pumped back to the same water system. The lining could possibly be justified on the grounds of energy savings. Similarly, the expansion of irrigated land down river at RID is not sustainable with surface water supplies. Even though groundwater levels are typically more than 100 m deep, pumping at RID continues.

Water capture and reuse. In more humid regions, rainfall provides most of the crop water requirement. Recent years have seen significant expansion in irrigation in the humid south because of the benefits of a few irrigations during critical water deficit periods, even when

annual rainfall exceeds crop water needs. The Grand-Prairie Irrigation Project in eastern Arkansas provides a good case study for examining water conservation issues in humid areas. The project consists of 98,400 cropped ha. Rice has been grown there since 1904. Groundwater withdrawals from confined groundwater aquifers that receive only limited recharge exceeded recharge as early as 1910 and groundwater levels have continued to decline since. In the late 1980's, the Grand Prairie irrigation district was formed to supplement water supplies for the project area.

A significant on-farm component was added to the project to help reduce the amount of water diverted from the river. Cost sharing for these improvements was 65%. These on-farm improvements included storage reservoirs at the high ends of farms and tailwater pits at the low ends of farms. Water is pumped into the reservoirs from groundwater, from the tailwater pits and from a river diversion. Water is released from the reservoirs to irrigate fields. The tailwater pits are situated in the natural drainage channels so that they can capture rainfall runoff and irrigation return flows. They are built with spillways so that excess water can flow downstream. Conservationists objecting to the project generally believed that low irrigation efficiencies in the area contributed to the groundwater decline and large diversions caused by low irrigation efficiencies would deplete the White River flow.

A study was conducted by the NRCS to evaluate the effectiveness of the proposed on-farm improvements to capture rainfall and to improve irrigation efficiencies on these systems (Robinson et al. 2003). This study evaluated water use on a small watershed consisting of seven farms, for which on-farm improvements had been planned as part of the project. On-farm

reservoirs and sumps are used to capture irrigation tailwater and rainfall runoff. One of the seven farms did not include improvements. It was possible, however, to capture runoff from this farm in tailwater pits on downstream farms. Total storage represented roughly 200 ha-mm/ha (8.4 ac-in/ac). The initial study modeled the hydrology of the area with the SPAW (Soil-Plant-Air-Water) model (Saxton 2002). A typical rice-soybean rotation was modeled using weather data for 1961-1966 to examine the impact of improvements. The output from SPAW was analyzed to assess specific impacts of reservoirs and tailwater sumps.

Results are shown in Tables 5 and 6, based on assumed values of field application efficiency. Because of extremely tight soils, groundwater recharge (even to surface aquifers) was nearly insignificant. Average crop consumptive use was 602 mm, with 216 mm coming from effective precipitation. The average irrigation water requirement was 386 mm. Sustainable groundwater use was estimated at 60 mm. First, Table 5 shows that the use of tailwater sumps resulted in farm irrigation efficiencies that were much higher than the field application efficiencies. Second, because water running off one farm is captured downstream, the efficiency from a watershed basis is also higher than the average farm irrigation efficiency. Under the pre-project conditions, essentially 100% of the irrigation requirement was supplied by groundwater pumping. Under most post-project scenarios, this draft of ground water can be cut in half. Table 5 shows that once the field application efficiency reaches roughly 70%, further improvements provide little benefit from a watershed basis. Table 6 shows that the net water supplied (applied minus recycled) hardly changes from 70 to 80% *AE* (418 versus 411 mm). This is because the sumps and reservoirs were able to manage the volume of water running off at these efficiencies, but at lower efficiencies there was excess water that could not be captured (i.e, this break point is a function

of infrastructure capacity). Low field application efficiencies result in considerably more recycling of the water.

With the project in place, this example watershed would be expected to meet crop water requirements, on average, with 1/3 coming from effective precipitation on the fields themselves, 1/3 coming from rainfall runoff captured and used for irrigation (during both the growing and non-growing seasons), and 1/3 coming from groundwater or river diversions. The rainfall runoff, if not captured, would add to Mississippi River flows that may already be at flood stages (i.e., mostly not recovered for consumption), and would have to be replaced by groundwater overdraft or White River diversions, which are controversial for environmental reasons. Thus these water conservation efforts are providing much more benefit than would be gained by just improving field application efficiencies. The program brings new supplies to the farms in the form of captured rainfall runoff and recycled irrigation runoff. If field application efficiencies were 50%, these on-farm improvements alone would be expected to save 5 ML/ha (500 mm) in groundwater pumping. As of 2003, actual on-farm improvements have been contracted on more than 24,000 ha, a quarter of the project area, for a cost of $35 million. The on-farm improvements are projected to be completed in 2010.

Salinity and In-stream Flow Issues. It is clear that from a simplistic point of view, that reducing diversions from the Colorado River in the Grand Valley of western Colorado will not conserve water. All excess flows (with the exception of minor evaporation and phreatophtye usage) eventually return to the river before it leaves the Grand Valley. However, the Grand

Valley of Colorado is confronted with the issue of increasing salt loads in the return flows to the Colorado River, either via the deep percolation water from fields or from canal seepage (by picking up salt from the underlying natural soil and rock formations). Furthermore, it is confronted with the challenge of maintaining minimum in-stream flows immediately downstream from the major diversion dams just upstream from the city of Grand Junction. A 15 mile stretch of river exists downstream from the irrigation district diversion dams – in which the flows are judged to be inadequate for fish, during certain times of the year.

For at least 25 years, large investments have been made in the Grand Valley to improve on-farm irrigation efficiencies – not focusing on the value to the farms in Grand Valley, but focusing on their impact, via salinity, on farms far downstream, in California, for example. Districts have converted sections of canal to pipelines, flow measurement devices have been installed at field turnouts, land has been graded, gated pipe purchased, surge irrigation practiced, and irrigation scheduling attempted. These all reduced the salt load in the downstream sections of the Colorado – not by "saving water" but by reducing the diverted volume and the resulting deep percolation through the underlying salty shale soil.

More recently, the 13-mile stretch of relatively dry river has been a concern. Fish and environmental advocates have paid for further modifications to the Government Highline Canal of the Grand Valley Water Users Association so that they can operate canal effectively with lower diversion flow rates in the canals. The district has almost eliminated all spills from the canal. These efforts have not saved water or impacted the salt loads downstream – but they have enabled more water to stay in the river locally in critical sections of river.

Benefits of Incidental Groundwater Recharge. The Eastern Snake River Plain (ESRP) of Idaho overlays a huge fractured basaltic aquifer that stretches nearly 300 km from near Yellowstone Park in the northeast to the Thousand Springs area in the southwest, which is a major discharge point for the aquifer. The aquifer contains a volume of water equivalent to the volume of Lake Erie. The aquifer system is bordered on the southern edge by, and is hydraulically connected to, the Snake River, a large river system supplied primarily by mountain snowmelt and aquifer discharge. There are a total of 850,000 ha (2.1 million acres) of irrigated land overlying the aquifer system, of which 450,000 ha are supplied by diverted river water and 400,000 ha by groundwater pumped directly from the aquifer. Beginning in about 1860, river diversions supplied surface water to farm application systems via canals and relatively 'inefficient' surface irrigation was practiced on farms. Since about 1970, about half (240,000 ha) of surface irrigation systems have converted to more efficient sprinkler systems. The "incidental" recharge stemming from the deep percolation of "excess" irrigation water from farms and seepage from canals has historically been the primary source of recharge to the ESRP aquifer, far exceeding recharge from water entering the aquifer via side tributaries and from natural precipitation (averaging only 250 mm/yr) over the plain. An annual recharge to the aquifer is roughly 9.9 km^3 (8.0 million Ac-ft/yr), which can be broken categorized as: incidental recharge from excess irrigation water (60%), tributary underflow (17%), precipitation (9%), river losses (9%), and other (5%). The influence of this incidental recharge can be seen from stream-flow records for the Snake River below the aquifer, which changed from a near constant 115 m^3/s in the early 1900s to more than 185 m^3/s in the 1960s Figure 8). Following that period, conversion of surface irrigation systems to more efficient sprinkler systems has reduced incidental recharge

to the ESRP aquifer, and, along with direct ground-water pumping for irrigation, has caused aquifer levels and discharges to the river to decline, being roughly 160 m^3/s in the 1990s. Declines in spring flows have impacted a large spring-fed trout aquaculture industry, as well as “senior” river water diverters (irrigators), with both groups now in litigation with ground-water pumpers.

Conclusions

While there are many situations where improvements in field application and irrigation efficiency do not increase the amount of fresh water available, there are cases where real water saving are possible from irrigation system improvements. Here are some general conclusions.

- Where irrigation water quality is good and deep-percolation returns to a freshwater aquifer, there may be little incentive, and sometimes disincentives, to reduce deep percolation.
- Where deep percolation water is of low quality or picks up salts from underlying soil and rock, reducing the amount of deep percolation saves fresh water.
- Where runoff returns to downstream surface water supplies, reducing runoff is only useful when water quality is degraded (e.g., from erosion) or if diversions can be reduced to protect in-stream flows immediately downstream of the diversion point.
- Storing and recycling rainfall and irrigation runoff can be an effective way to save freshwater, if such runoff is not already recaptured for other uses downstream.
- Reducing irrigation diversion amounts can save fresh water if return flows do not augment surface supplies for other uses.

- Irrigation diversions which return to surface water systems change the timing of stream flows, which sometimes is an environmental benefit and sometimes is an environmental liability.
- Improvements in field irrigation systems usually improve field irrigation efficiency, sometimes increase yields and increase water consumption, and usually improve productivity of land and water.
- Taking irrigated land out of production is often the only way to save substantial volumes of fresh water by reducing the consumptive use component, but often only the consumed water is saved (i.e., not all of the diverted water.)
- Methods to reduce non-beneficial evaporation and phreatophyte *ET* are an untapped source for agricultural water conservation in some cases.

State water law, interstate compacts, and local water rights can substantially impact the outcome of water 'conservation' programs, and the parties that benefit from any localized 'savings.' Many western water law systems allow for a single diverter or group of common diverters to make internal improvements to their systems to capture existing internal flows of 'excess' water (i.e., their 'losses') and to put this water to beneficial use within the existing boundaries of their application area (i.e., no 'expansion' of the water right is allowed). Therefore, from an individual diverter's perspective, a conservation program may in fact increase their water supply. However, hydrologically, no new water may be created to the total basin water supply, and downstream users outside the domain of the conservation 'program' may suffer a reduced supply. In some cases, conservation programs have reduced water consumption resulting in increased flows in systems, only to see these flows diverted by third parties who have existing, higher priority 'rights' that allow them to legally divert any waters appearing in the stream.

Notation

AE	Application efficiency
CV	Coefficient of variation
EC	Electrical conductivity
ET	Evapotranspiration
IE	Irrigation efficiency
ICUC	Irrigation consumptive use coefficient
LR	Leaching requirement

References

Allen, R.G., C. Burt, A.J. Clemmens, and L.S. Willardson (1996), Water conservation definitions from a hydrologic viewpoint. Proc. North American Water and Environment Congress, ASCE, Anaheim, CA, (CD-ROM)

Allen, R.G., L.S. Willardson, and H. Frederiksen. (1997), Water use definitions and their use for assessing the impacts of water conservation. Proceedings ICID Workshop on Sustainable Irrigation in Areas of Water Scarcity and Drought (J.M. de Jager, L. P. Vermes, R. Ragab (ed)). Oxford, England, Sept. 11-12, pp 72-82.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith (1998), "Crop Evapotranspiration: Guidelines for computing crop water requirements." Irrig. and Drain. Paper 56, Food and Agriculture Organization of the United Nations, Rome, 300 pp.

Allen, R.G., L.S. Willardson, C. Burt, and A.J. Clemmens (2003), Water conservation questions and definitions from a hydrologic perspective. Proc. International Association Conference, San Diego, CA. 12 p. (on CD).

Ayars, J.E. and R.A. Schoneman (2006) Irrigating field crops in the presnence of saline groundwater. Irrigation and Drainage 55(3), 265-279.

Ayers, R.S. and D.W. Westcot (1985), Water quality for agriculture. Irrigation and Drainage Paper No. 29, Rev. 1, FAO, Rome, Italy.

Bathurst, V.M. (1988), Wellton-Mohawk on-farm irrigation improvement program post-evaluation report. U.S.D.A., Soil Conservation Service, Phoeniz, AZ. 40 p.

Bennett, J., A. Blum and G.S. Khush (2007) Can genetics and biotechnology create more crop for less water? Presented at the 2007 Annual Meeting, American Academy for the Advancement of Science, San Francisco, CA, 15-19 February.

BoR (1964-2004), Compilation of records in accordance with Article V of the decree of the Supreme Court of the United States in Arizona v. California et al. Dated March 9, 1964. (Individual reports by calendar year) Boulder Canyon Operations Office, Bureau of Reclamation, Boulder City, NV.

BoR (1990), Water budgets for the Weelton-Mohawk Irrigation and Drainage District (WMIDD) – updated to include calendar year 1990, Water Operations Division, Lower Colorado Region, Bureau of Reclamation, Boulder City, NV.

Brendecke, C. (2004), Idaho ground water appropriators, Inc. Presentation to Eastern Snake Plain Aquifer Working Group. Burley, Idaho, April 22, 2004.

Burt, C.M. (2006) Ag-Irrigation Management. Irrigation Trainaing and Research Center, Cal Poly, San Luis Obispo, CA 93407.

Burt, C. M., A.J. Clemmens, T.S. Strelkoff, K.H. Solomon, R.D. Bliesner, L.A. Hardy, T.A. Howell, and D.E. Eisenhauer (1997), Irrigation performance measures -- efficiency and uniformity. *J. Irrig. and Drain. Eng. 123(6)*, 423-442.

Burt, C.M., A.J. Mutziger, R.G. Allen, and T.A. Howell (2005), Evaporation research: Review and interpretation, *J. Irrig and Drain. Engr. 131(1)*, 37-58.

Cai, X. and M.W. Rosegrant (2007) Optimal water development strategies for the Yellow River Basin: Balancing agricultural and ecological water demands. Water Resources Research, 40, W08S04, doi:10.1029/2003 WR002488.

Clemmens, A. J. and D.J. Hunsaker (1999), ET components and how they contribute to irrigation efficiency. In Proc. International Water Resources Engineering Conference, ASCE, Seattle, WA, Aug. 8-11, 1999. (CDROM).

Clemmens, A. J. and D. J. Molden. Water uses and productivity of irrigation systems. Irrigation Science. 25(3), 247-261.

Doorenbos, J. and W.O. Pruitt (1977), Guidelines for predicting crop water requirements," Irrig. and Drain. Paper 24, (1st and 2nd ed). Food and Agriculture Organization of the United Nations, Rome, 179 and 156 pp.

Erie. L.J., O.F. French, D.A. Bucks, and K. Harris (1982), Consumptive use of water by major crops in the southwestern United States. Conservation Research Report No. 29, Agricultural Research Service, USDA, Washington, DC. 42 p.

Evans, R.G. and E.J. Sadler (2007), New methods and technologies to increase water-use efficiencies, Water Resources Research (Submitted as companion paper).

Hanson, B.R. and J.E. Ayars (2002) Strategies for reducing subsurface drainage in irrigated agriculture through improved irrigation. Irrigation and Drainage Systems 16(4), 261-277.

Howell, T.A., A.D. Schneider, and D.A. Dusek (2002), Effects of furrow diking on corn response to limited and full sprinkler irrigation. *Soil Sci Soc Am J. 66*, 222-227.

Huffaker, R. (2007) The paradox of agricultural water conservation policy, Water Resources Research (submitted as companion paper)

Hutson, S.S., N.L. Barber, J.F. Kenny, K.S. Linsey, D.S. Lumia, and M.A. Maupin (2004), Estimated use of water in the United States in 2000. USGS Circular 1268, http://water.usgs.gov/pubs/circ/2004/circ1268/ http://water.usgs.gov/pubs/circ/2004/circ1268/htdocs/text-ir.html

Keller, A.A. and J. Keller (1995), Effective efficiency: a water use efficiency concept for allocating freshwater resources. Discussion paper 22, Center for Economic Policy Studies, Winrock Int., Arlington, VA. 19 p. also in USCID Newsletter, United States Committee on Irrigation and Drainage, Issue No. 71, Jan. 1995.

Letey, J. and G.L. Feng (2007), Dynamic versus steady-state approaches to evaluate irrigation management of saline waters. Agricultural Water Management, 91(1-3), 1-10.

Letey, J., C.F. Williams and M. Alemi (2002) Salinity, drainage and selenium problems in the western San Joaquin Valley of California. Irrigation and Drainage Systems 16(4), 253-259.

McBean, E.A. and E. Bautista (1995) California's Emergency Water Bank: Potential for Environmental Impacts. Canadian Water Resources Journal. 20(3): 171-184.

Molden, D. 2007 Water for food Water for life A Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute, Colombo, Sri Lanka, and Earthscan, London.

Molden, D.J., R. Sakthivandivel and J. Keller (2001) Hydronomic Zones for Developing Basin Water Conservation Strategies. Research Report 56, International Water Management Institute, Colombo, Sri Lanka.

NASS (2002) Census of Agriculture 2002. National Agricultural Statistics Service. http://www.nass.usda.gov/Census_of_Agriculture/index.asp http://www.nass.usda.gov/census/census02/volume1/us/index1.htm http://www.nass.usda.gov/census/ http://www.nass.usda.gov/census/census02/volume1/us/index1.htm

Rice, R. C., D.J. Hunsaker, F.J. Adamsen, and A.J. Clemmens (2001), Irrigation and nitrate movement evaluation in conventional and alternate-furrow irrigated cotton. *Trans. ASAE 44(3)*, 555-568.

Robinson, P., A.J. Clemmens, D.K. Carman, Z. Dalmut, and T. Fortner (2003), Irrigation development in eastern Arkansas: water supplies, uses, and efficiencies. p. 283-292. In 2nd Int. Conf. on Irrig. & Drain, Phoenix, AZ, May 12-15, 2003.

Saseendran, S.A., L.R. Ahuja, T.J. Trout, L. Ma, and D.C. Nielsen (2007) Use of system models to evaluate limited irrigation management options for corn in a semi-arid environment (Submitted as companion paper).

Saxton, K. (2002), SPAW Soil-plant-air-water field and pond hydrology version 6.1.25. Agricultural Research Service, Pullman, WA.

Snyder, R.L., B.J. Lanini, D.A. Shaw, and W.O. Pruitt (1989), Using reference evapo-transpiration (ETo) and crop coefficients to estimate crop evapotranspiration (ETc) for agronomic crops, grasses, and vegetable crops. Coop. Ext., Univ. of Calif., Berkeley, CA, Leaflet No. 21427, 12 p.

Styles, S.W. (1993), On-Farm Irrigation Efficiency. Special Technical Report for Imperial Irrigation District, Boyle Engineering Corp., Imperial, CA.

USDI (2005), Quality of Water, Colorado River Basin, Progress Report No. 22. U.S. Department of Interior, Washington, D.C.

Wallender, W., J. Rhodes, M. Weinberg, S. Lee, C. Uptain and D.Purkey (2002) Irrigated land retirement. Irrigation and Drainage Systems 16(4), 311-326.

Willardson, L.W., R. G. Allen, and H. Frederiksen (1994), Eliminating irrigation efficiencies. USCID 1994 Meeting, Stapleton Plaza, Denver, CO. 15 p.

Willardson, L.S. and R.G. Allen. (1998), Definitive basin water management. 14th Technical Conference on Irrigation, Drainage and Flood Control, USCID (J.I. Burns and S.S. Anderson (ed))., June 3-6, 1998, Phoenix, Arizona. p. 117-126

Wright, J.L. (1982), New Evapotranspiration Crop Coefficients. *J. Irrig. and Drain. Div., ASCE, 108*, 57-74.

Table 1. Average water use before and after Wellton-Mohawk On-farm Irrigation Improvement Program (Bathurst 1988) on 19,278 ha.

Crop	Water_Use	Water_Use	Basal_ET*	Basal_ET/Water_use	Basal_ET/Water_use
"null"	(mm)	(mm)	(mm)	(Ratio)	(Ratio)
"null"	Before	After	"null"	Before	After
Alfalfa	3,124	2,362	1,880	0.60	0.80
Cotton	1,676	1,346	1,047	0.62	0.78
Wheat	1,194	813	660	0.55	0.81

*From Erie et al. (1982)

Table 2. Average crop yields before and after Wellton-Mohawk On-farm Irrigation Improvement Program (Bathurst 1988) on 19,278 ha.

Crop	Units	Before	After	Difference	Percent_Difference
Alfalfa	Mg/ha	3.1	3.5	0.4	12%
Cotton-lint	Kg/ha	212	238	26	12%
Wheat	Mg/ha	6.1	7.4	1.2	20%

Table 3. Water balance for the Wellton-Mohawk Valley.

Period	Years	Diversion	Return_flow	Consumptive_use	ICUC
"null"	"null"	(km^3)	(km^3)	(km^3)	"null"
Pre	1964-1975	0.616	0.252	0.364	0.591
During	1976-1986*	0.523	0.192	0.331	0.634
During[1]	1976-1986	"null"	"null"	0.380	0.764
Post	1987-2004*	0.515	0.163	0.352	0.684

*excluding flood affected years 1979, 1980 and 1993.
[1] from detailed water balance, rather than decree accounting

Table 4. Water use for the Wellton-Mohawk Valley.

Period	Years	Area	Diversion	Return_flow	Consumptive_Use
"null"	"null"	(ha)	(m)	(m)	(m)
Pre	1964-1975	26950	2.26	0.92	1.34
Post	1987-2004*	25110	2.03	0.64	1.39

*excluding flood affected years 1979, 1980 and 1993.

Table 5. Efficiencies under post-project conditions for a 7-farm watershed in Arkansas.

Field Application Efficiency (assumed)	Average_Farm Irrigation Efficiency "null"	Range_in_Farm Irrigation Efficiencies "null"	Watershed Irrigation Efficiency "null"	Groundwater pumped_as_a fraction_of ET_{iw}	Rainfall_runoff captured_as_a fraction_of ET_{iw}
50%	84%	50-91%	87%	0.68	0.47
60%	88%	60-92%	90%	0.51	0.60
70%	90%	70-93%	92%	0.46	0.63
80%	92%	80-94%	94%	0.44	0.62

Table 6. Water sources for different field application efficiencies for a 7-farm watershed in Arkansas.

Field Application Efficiency (assumed) "null"	Total_water applied_at head_of_field "null" (mm)	Groundwater pumped_or river_water diverted (mm)	Rainfall_runoff captured_and applied "null" (mm)	Recycled Water "null" "null" (mm)	Applied minus recycled water (mm)
50%	760	264	182	314	446
60%	638	198	233	208	430
70%	545	178	241	127	418
80%	477	170	241	66	411

Figure Captions

Figure 1. Predominant water inflows and outflows for irrigation systems where components 1-5 are 1--Water consumed by the crop within the area for beneficial purposes, 2--Water consumed within the area under consideration but not beneficially, 3--Water that leaves the boundaries of the area under consideration but is recovered and reused, 4--Water that leaves the boundaries of the area under consideration but is either not recoverable or not reusable, and 5--Water that is in storage within the boundaries.

Figure 2. Adding extra water results in less of the field receiving too little water. CV = 20%.

Figure 3. Improving the uniformity results in less extra water required and less deficit in the area receiving an inadequate supply.

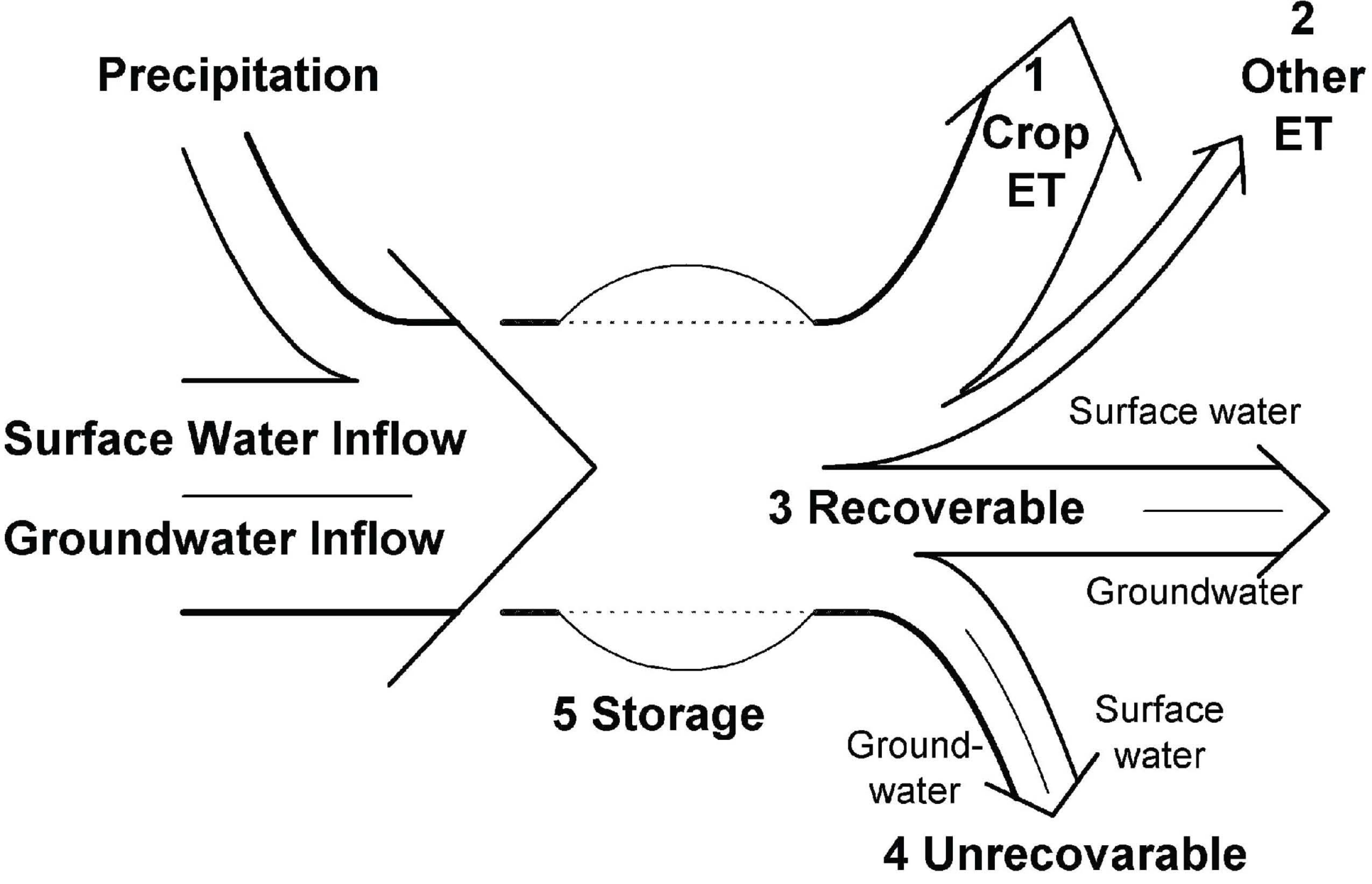
Figure 4. Water and salt budgets for irrigation systems having a conservative salt balance, for consumed fractions of 60% and 75%.

Figure 5. Water and salt budgets for irrigation systems that are extracting salts via deep percolation through saline geologic formations, for consumed fractions of 60% and 75%.

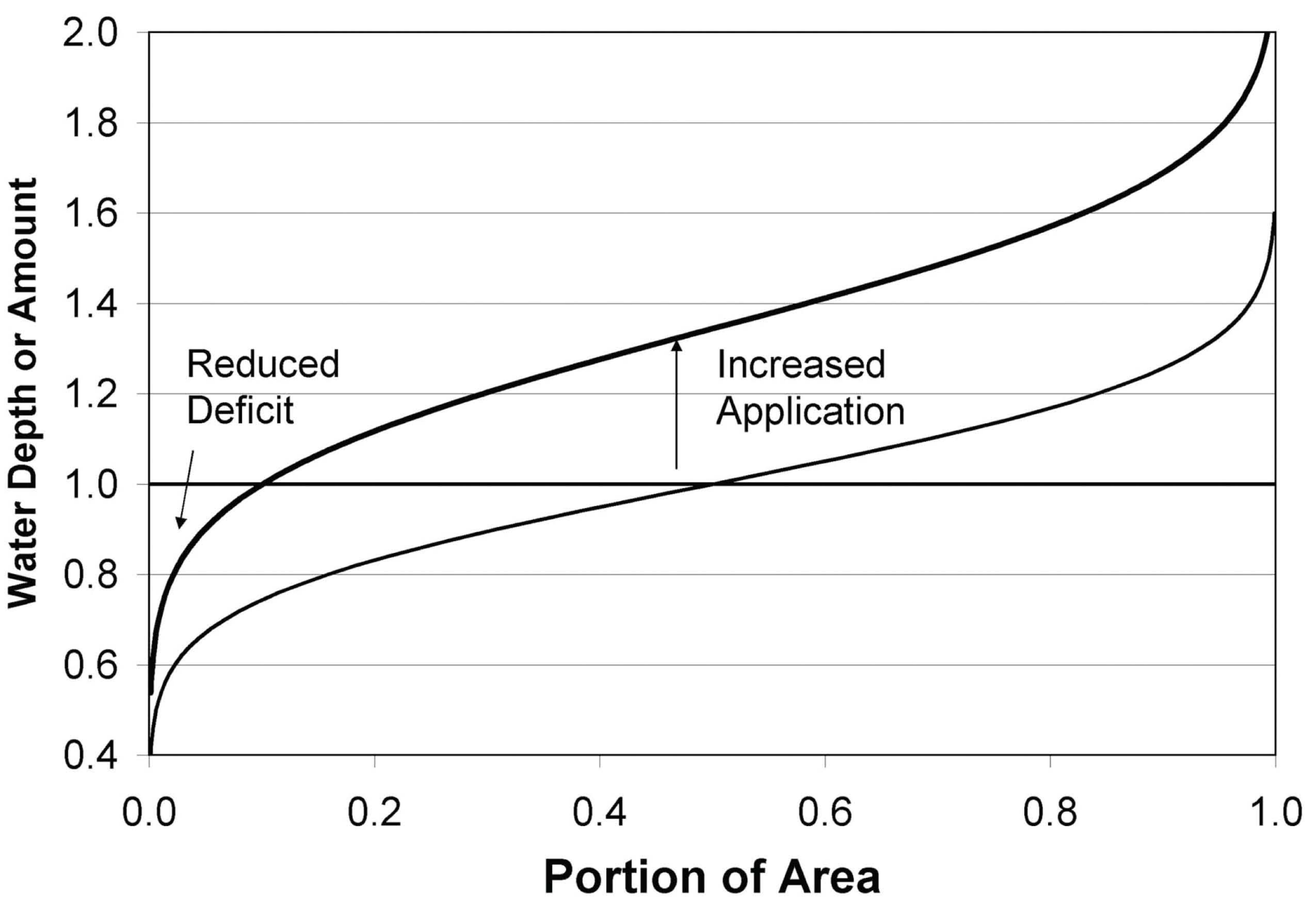
Figure 6. Application and irrigation efficiencies for sloping furrow cotton field, 1994. (From Rice et al. 2001).

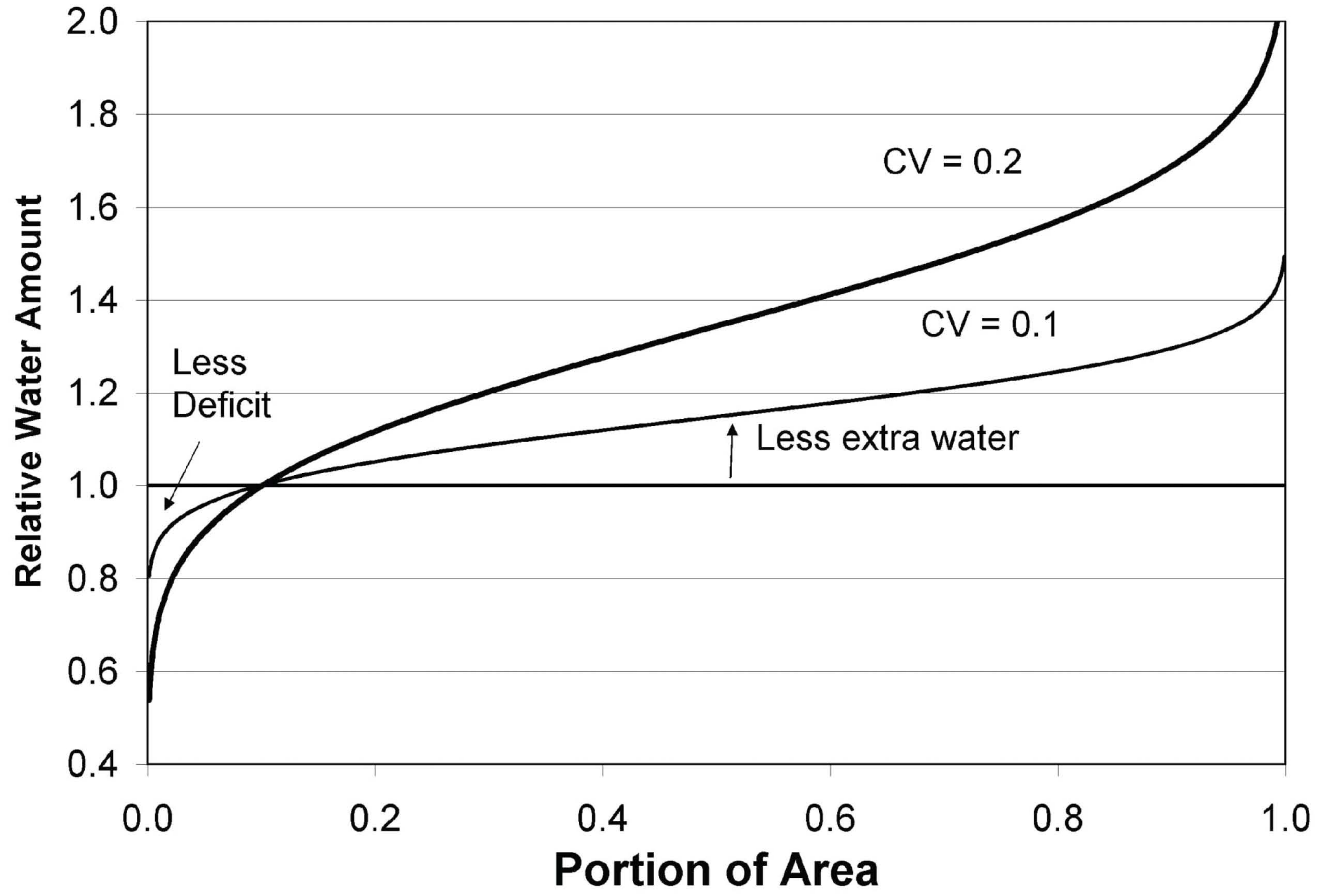
Figure 7. Irrigation consumptive use coefficient for Wellton-Mohawk Valley based on diversions less returns and based on a detailed water balance.

Figure 8. Annual mean aquifer discharge to the Thousand Springs reach of the Snake River from 1902 through 2002, showing the downward trend since 1950 due to direct ground-water pumping and from reduced recharge stemming from conversion to more efficient irrigation systems that use river water (from Brendecke, 2004).

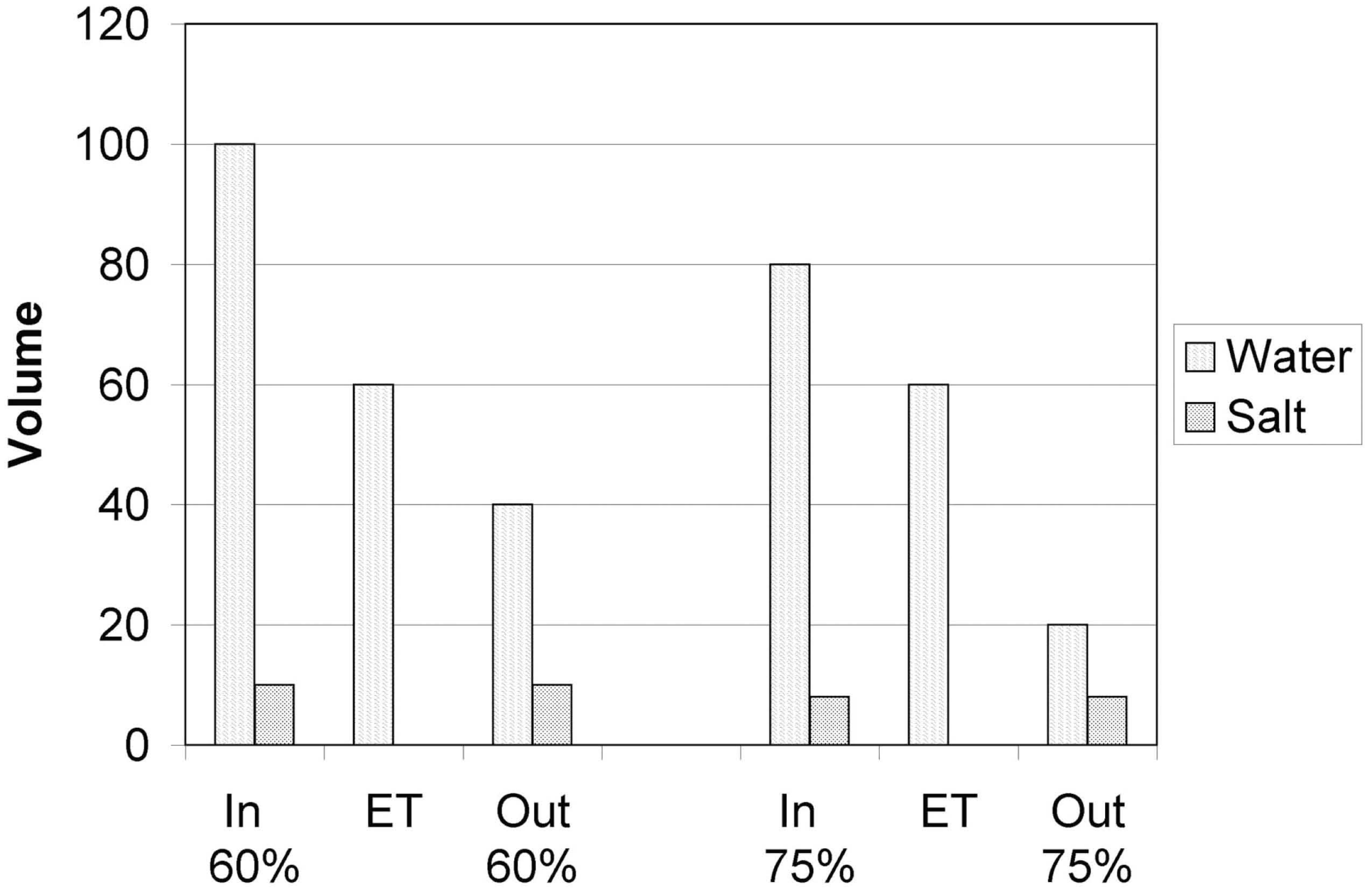


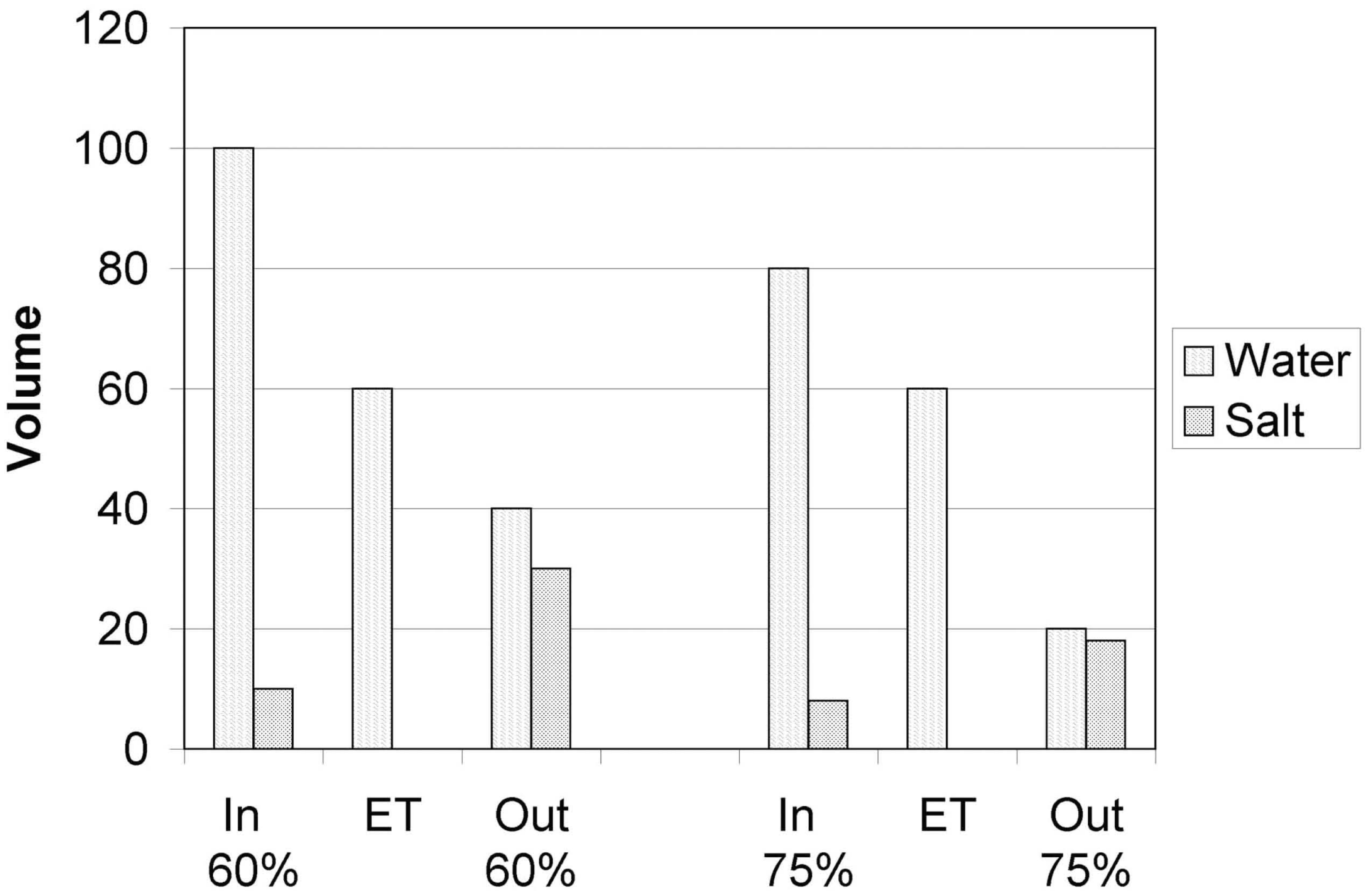
Precipitation
1
Crop
ET
2
Other
ET
Surface Water Inflow
Groundwater Inflow
Surface water
3 Recoverable
Groundwater
5 Storage
Surface
water
Ground-
water
4 Unrecovarable

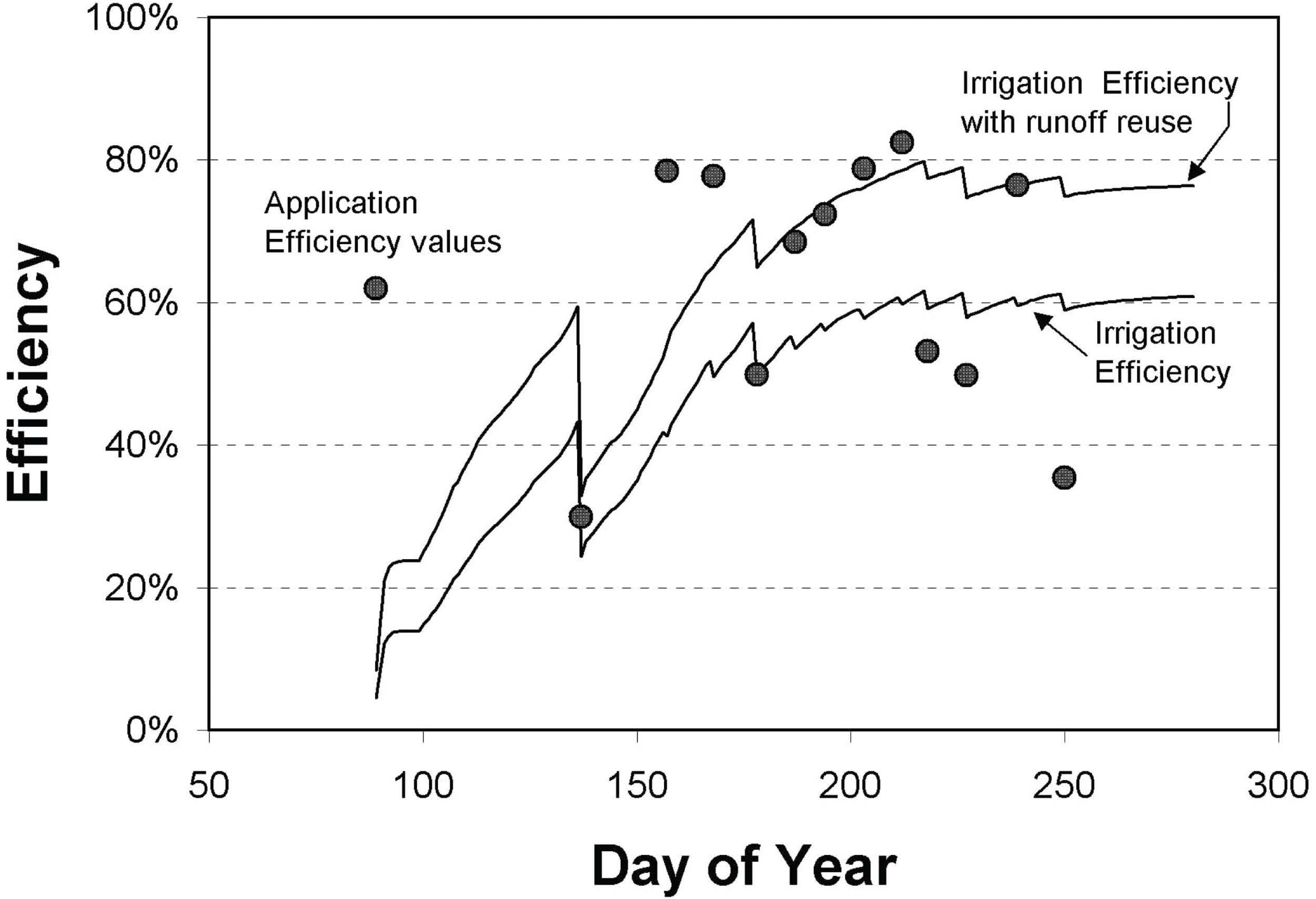

Water Depth or Amount
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
Reduced
Deficit
Increased
Application
0.0
0.2
0.4
0.6
0.8
1.0
Portion of Area

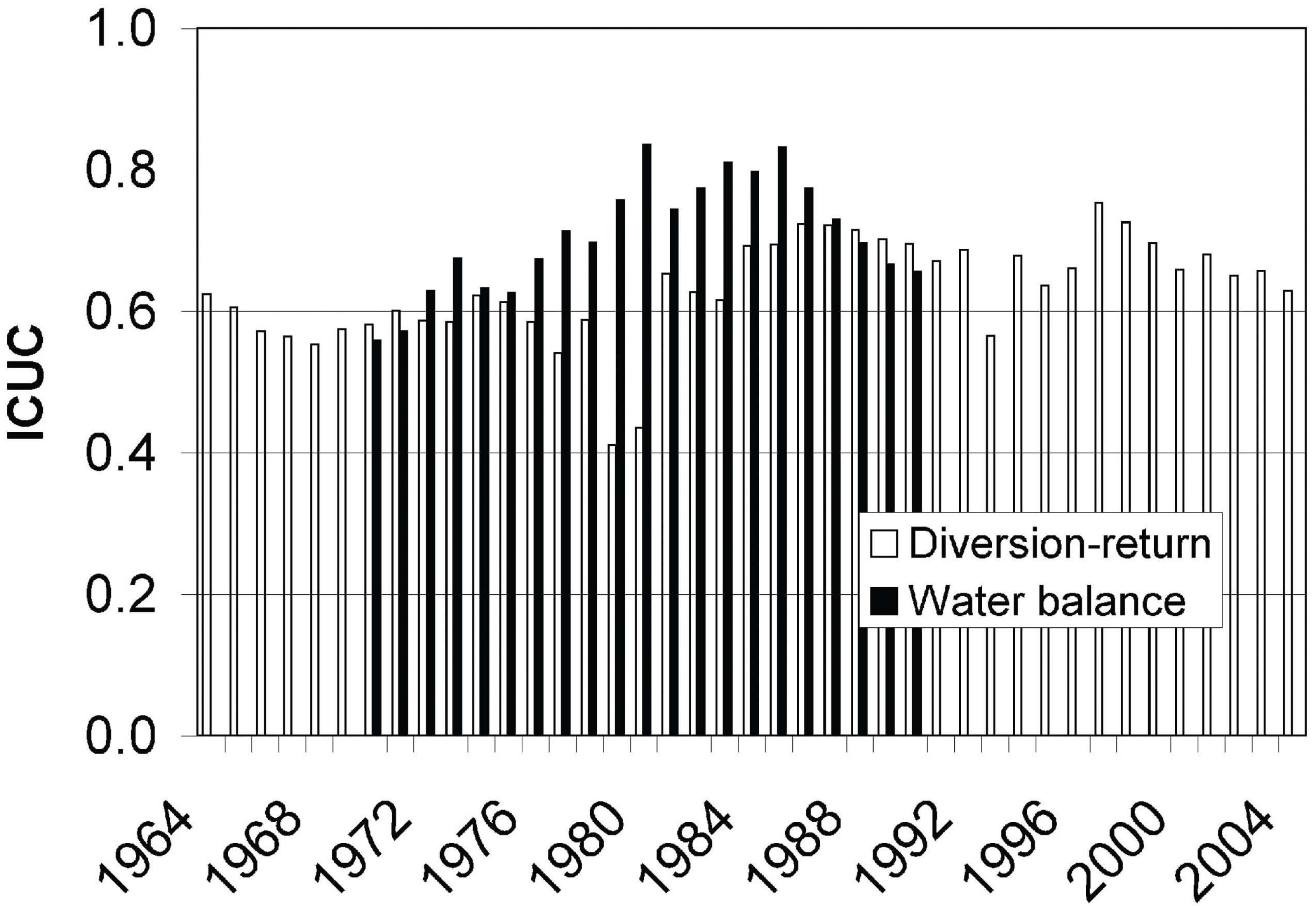


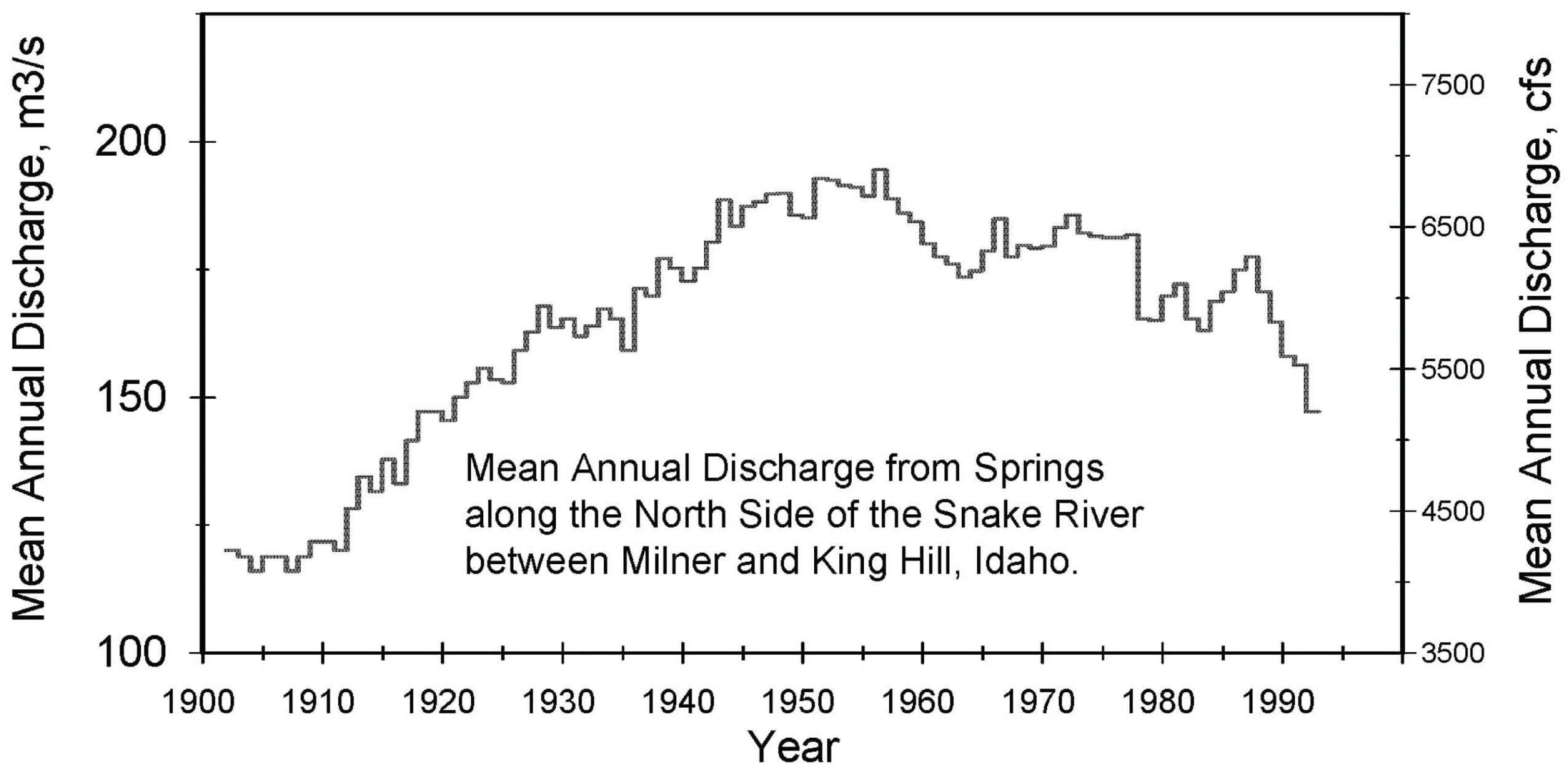
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
Relative Water Amount
CV = 0.2
CV = 0.1
Less
Deficit
Less extra water
0.0
0.2
0.4
0.6
0.8
1.0
Portion of Area


120
100
80
60
40
20
0
Volume
Water
Salt
In 60%
ET
Out 60%
In 75%
ET
Out 75%


120
100
80
60
40
20
0
Volume
Water
Salt
In
60%
ET
Out
60%
In
75%
ET
Out
75%


100%
80%
60%
40%
20%
0%
Efficiency
Application
Efficiency values
Irrigation Efficiency
with runoff reuse
Irrigation
Efficiency
50
100
150
200
250
300
Day of Year


1.0
0.8
0.6
0.4
0.2
0.0
ICUC
Diversion-return
Water balance
1964
1968
1972
1976
1980
1984
1988
1992
1996
2000
2004


Mean Annual Discharge from Springs
along the North Side of the Snake River
between Milner and King Hill, Idaho.
Mean Annual Discharge, m3/s
200
150
100
Mean Annual Discharge, cfs
7500
6500
5500
4500
3500
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year