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Brad Udall

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1 Project Overview

The Colorado River Basin has been under substantial stress since 2000. Growing cities, the Lower Basin's Structural Deficit[1], the ongoing, unprecedented 17-year-long drought, and recently recognized environmental flow needs are at the root of this stress. The high likelihood of long-term flow declines due to climate change is also forcing serious re-thinking of the long-term sustainability of the basin's water demands and supplies. All of these issues were identified in the long-term supply-demand imbalance identified by Reclamation's Basin Study in 2012 that projected a potential 3 million acre-feet/year gap by the year 2060. As increasing water scarcity occurs in the Colorado River Basin, water users looking for new sources of supply have focused on the largest water user in the basin, agriculture.

The default solution to many of these problems is to transfer water from the cheapest and most plentiful source — agriculture — to supply new water demands in the region. However, if pursued in haste, and without sufficient information, the likely outcome may be permanent fallowing, along with serious economic disruption to agricultural communities, loss of valuable farmland, loss of important amenity values, and a loss of a sense of place in many rural communities within the basin.

In 2015 the Colorado Water Institute undertook a Walton Family Foundation funded project entitled "Agricultural Water Conservation in the Colorado River Basin: Alternatives to Permanent Fallowing Research Synthesis and Outreach Workshops". This project was undertaken to explore ways to minimize harm to agriculture if transfers occur. Four detailed synthesis reports of the four common methods used to temporarily transfer water from agriculture were produced by the project. The water saving methods covered by the reports are:

- Deficit irrigation of Alfalfa and other forages
- Rotational fallowing
- Crop switching
- Irrigation efficiency and water conservation

After the reports were drafted, three workshops were held, one in the Upper Basin located in Grand Junction, Colorado on November 4, 2016, one in the Lower Basin in Tucson, Arizona on March 29, 2017, and one in Washington, D.C. on May 16, 2017 to disseminate the findings. Over 100 people attended these workshops.

This document summarizes the most important findings from the individual reports on the four water saving options. Each report offers an up-to-date synthesis and analysis regarding the best-known and most promising methods of agricultural water savings along with case studies. The complete reports are available on the Colorado Water Institute's website (http://cwi.colostate.edu/).

2 Deficit Irrigation Summary

Irrigation is generally designed to meet the full water requirements of crops. ***Deficit irrigation*** is the generic term for applying less water than the full needs of a crop; it can take many forms. It can be a

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[1] The Structural Deficit is a 1.2 million acre-feet/year imbalance between the average flow into Lake Mead and the average flow out of Lake Mead. This imbalance drives Lake Mead lower by about 12 feet per year. It also serves to drive Lake Powell lower through complex rules that attempt to balance the contents of the two reservoirs.

planned, sophisticated strategy or an unplanned, natural consequence when water scarcity arises. Planned deficit irrigation is widely used with grapes to improve quality. Unplanned deficit irrigation occurs commonly on forage crops that depend on diversions from mountain streams as the runoff pulse declines in late summer.

2.1 Different Methods of Planned Deficit Irrigation

Regulated Deficit Irrigation (RDI) is the term used to apply less water than needed during less critical life stages, with the general goal of improving the quality of the crop. RDI is practiced widely on certain crops like fruit and nut trees.

Another planned deficit irrigation strategy is used with perennial hay crops, especially alfalfa. By completely ceasing water application for part of the year, some perennial crops can be forced to enter dormancy and thus survive a lack of water. This method has been most consistently called "**split season" deficit irrigation.**

2.2 Why Alfalfa and Deficit Irrigation?

Alfalfa, because of its large consumptive use relative to other crops, its extensive acreage in both the Lower and Upper Basins, and its ability to go dormant when water is removed, is an obvious candidate for saving water through deficit irrigation. Although it is also possible to partially irrigate alfalfa throughout the growing season, split season irrigation results in higher relative yields, better quality, and lower labor than other forms of deficit irrigation, and thus has been the focus of almost all deficit irrigation studies.

2.3 Alfalfa's Importance in the Colorado River Basin

Alfalfa, when combined with all hays, is the nation's third largest crop by production value. It is very commonly grown in the West, where nearly 40% of the nation's alfalfa hay is produced from 11 western states. Because it is an animal food, it is sometimes called the "corn and soybeans" of the West. It is a major crop in each of the Colorado River Basin states and is 28% of the total acreage in the basin in these states. In most years, it makes up more acreage than any other crop in the Imperial and Palo Verde Valleys of California. Alfalfa is an important crop in a rotation because it is a nitrogen-fixing legume.

2.4 Critical Alfalfa Facts

Alfalfa yields range from under two tons per acre in the high mountain valleys of Colorado and Wyoming where only one cut is done, to over 10 tons per acre with 10 cuts per year in the low deserts of the Colorado River Basin. Harvesting and field drying is the one area where alfalfa has elevated risk for the grower because for storage, the hay must be dry. The plants last for several years in the field, especially if a dense stand with little room for weeds is established. Few pesticides and herbicides are used. The soil is left unplowed several years, for a positive effect on soil health. Alfalfa fixes nitrogen and thus the crop rarely needs nitrogen and it also provides nitrogen for the next crop. Because alfalfa fields are left undisturbed for years, they have significant wildlife benefits not present with annual row crops. Alfalfa is very easy to grow. It is adaptable to different climates from sweltering deserts to the highest mountain valleys, and can be planted at different times of the year.

Alfalfa is a cool season crop, meaning it is optimized to grow in the colder parts of the year. The spring and fall generate the highest yields, and the highest nutritional content. In Arizona, the term "summer slump" historically was used to mean the period in July and August when alfalfa generated little yield while using lots of water. In the 1960s before laser leveling, it was common to deficit irrigate during this period to save water ("summer dry down"), and to avoid root scalding from water ponding in fields when temperatures are above 100 degrees Fahrenheit.

2.5 Alfalfa's Important Ties to the Beef and Dairy Industries

Alfalfa is a critical input to the beef and dairy industries. Since 1970, the dairy industry in the West has grown enormously, and alfalfa production has commensurately increased. The number of dairy cattle has increased significantly in California, central Arizona, southeastern New Mexico, and the Front Range of Colorado. In California, alfalfa is a $1B/year crop feeding a $5B/year dairy industry, the largest agricultural sector in the state. California is now the number one dairy state, while New Mexico (#9), Arizona (#13), Colorado (#15), and Utah (#21) are also key national dairy producers. Alfalfa is grown where it is used because it is bulky and hence has a relatively high cost of transportation. It provides significant nutritional advantages compared to other forages with its high protein content.

2.6 Alfalfa Deficit Irrigation Studies

There have been numerous studies on deficit irrigation of alfalfa dating to the 1960s. Alfalfa has a natural ability to go dormant when water is reduced or cut off. Stand loss, the loss of some of the plants, has occurred in a few studies. Stand loss is especially related to sandy soils with little water holding capacity, and lengthy deficit irrigation periods during very high temperatures. In general, yield returns quickly once irrigation resumes and the hay quality does not appear to be affected. Deeper soils are generally better when water is cut off as they hold more water. Alfalfa's deep taproot can often obtain at least some water to keep the plant alive with deep soils.

2.7 Deficit Irrigation of Pasture

Irrigated pasture makes up approximately 15% of all irrigated lands in the 11 Western states. There is very little research on deficit irrigation of the grasses present in these pastures. Cow-calf operators are highly dependent on this resource. Grasses can also go dormant, but have much shallower root systems and are thus unable to tap deep moisture like alfalfa.

2.8 Case Studies

There are several recent case studies on deficit irrigation in the Colorado River Basin. The Colorado Water Trust has been pursuing its use in southwestern Colorado. The Colorado Compact Water Bank workgroup has been studying this issue as a way of saving water for post compact water rights in the event of an Upper Basin "compact call"[2]. Additionally, the recent Colorado River System Conservation Pilot Program has utilized deficit irrigation in the Upper and Lower Basins. Colorado State University has

[2] The Colorado River Compact contains a provision stating that the Upper Basin shall not deplete the flows of the river below 75 million acre-feet every ten running years. Were this to occur, the Upper Basin would have to reduce consumption and this reduction has been likened to an in-state river "call". In a river call, diversions from junior users are reduced in order to supply water to more senior users. Upper Basin "post compact" water rights – those with priority dates after the compact – would in theory be subject to curtailment under this "compact call" scenario.

studied this issue in both the Colorado's Arkansas and South Platte Basins, and studies are ongoing in the Colorado River Basin.

3 Rotational Fallowing Summary

Rotational fallowing, also known as lease-fallowing, is the act of temporarily fallowing farm land to save water for other purposes. Rotational fallowing has been used for more than 25 years in the Colorado River Basin. Unlike some of the other methods of saving water, such as crop switching and deficit irrigation, temporary land fallowing is a proven, successful strategy for conserving significant amounts of water with a long history of on-the-ground projects in the Colorado River Basin. Although there can be significant issues with quantifying the actual water savings from fallowing, there is little doubt that fallowing does save water.

3.1 Negotiations are Complex

Leasing-fallowing negotiations often take a long time before finding a successful combination of price, land, water amounts, agreement length, and other terms. These agreements are three-party agreements with each party -- the buyer, the sellers, and the irrigation district – having distinct needs. The Metropolitan Water District of Southern California (MWD) – Palo Verde Irrigation District (PVID) agreement in 2004 was preceded by a two-year trial, nearly ten years earlier. Persistence has been key for the Colorado's Lower Arkansas Valley Super Ditch[3] which suffered several false starts but now has on-the-ground projects. Fallowing in the Imperial Irrigation District was part of the larger California Quantification Settlement Agreement in 2003. The agreements are unique to each area and cannot easily be replicated. Efforts generally require complex negotiations, multiple studies on environmental and tax consequences among others, and complicated legal documents to enact.

3.2 Impacts to Nearby Communities

Fallowing agreements need to consider the impact to nearby communities. Agricultural communities and irrigation districts have important economic ties and the impacts of fallowing go beyond the irrigation district and individual farmers. Local agricultural suppliers can suffer from decreased purchases of crop inputs and services, as well as the displacement of jobs associated with the fallowed fields. Other, broad third-party impacts are also in play, including decreased retail sales, sales taxes, and property taxes, which can negatively impact and harm the overall community. In some recent fallowing agreements, relatively large community funds provided by the purchaser have been a part of the arrangement to provide economic support and mitigation for displaced individuals and businesses.

3.3 Agronomic Advantages and Disadvantages of Rotational Fallowing

Rotational fallowing to conserve water should provide many of the benefits of traditional land fallowing for soil health, future yield increases and pest management. These benefits, however, have been much less studied than the water conservation savings, and remain mostly unquantified. Rotational fallowing could be part of a larger, purposeful crop rotation plan to provide these additional benefits, while producing income for a farmer from a fallowed field.

One negative soil impact seems clear. In areas with salty subsurface moisture, which includes most areas

[3] The term "Super Ditch" implies a single physical ditch. The program is, in fact, a joint effort of shareholders on multiple existing ditches in the region.

in the Colorado River Basin, capillary action can move subsurface salt to the soil surface during fallowing and hence a pre-planting leaching irrigation to remove these salts following the fallowing period is often necessary. This leaching water reduces the water savings from fallowing, to the extent that it was not otherwise needed.

3.4 Field Management Issues

All fallowing programs require that bare fields be managed to prevent weeds, avoid topsoil erosion, and control dust. Most agreements require the landowners to sign documents stating that they will perform this work at their cost, or else fallowing payments will be either reduced or withheld. Monitoring efforts need to make sure that the enrolled fields are actually fallowed, and that proper land management activities are undertaken.

3.5 Quantification of Water Savings

Quantifying the water savings of fallowing can be complicated. Several different approaches have been used. A generic, but difficult approach, would be to make assumptions about the exact crop that would have been grown, its expected yield (thus, total crop consumptive water use) reduced by precipitation supplied by nature. In small fallowing arrangements, a per-acre water savings has often been stipulated. In large irrigation districts with substantial acreage devoted to fallowing such as PVID, the difference in headgate diversions in fallowed years versus non-fallowed years, minus assumed return flows, can be used as an approximation.

In Colorado's Arkansas River Basin, the State Engineer developed a spreadsheet-based tool to perform calculations on each enrolled tract to determine consumptive use, and the return flows needed to keep downriver users whole.

3.6 Case Studies

Rotational Fallowing was originally pursued by the Metropolitan Water District of Southern California in the Palo Verde Irrigation District in the early 1990s. This test case led to a 35-year agreement signed in 2004. Total fallowed acreage has ranged from 6500 to almost 40,000 acres[4] with water savings ranging from 25,000 to almost 120,000 acre-feet per year. Metropolitan has more recently pursued a small test summer fallowing with the Bard Irrigation District near Yuma. As part of its agreement with the San Diego County Water Authority, since 2003 the Imperial Irrigation District has also been fallowing lands to provide mitigation flows into the Salton Sea with over 700,000 acre-feet generated for the Sea and another 700,000 acre-feet for municipal purposes. This fallowing ends in 2017, with further municipal deliveries to San Diego provided by efficiency improvements. In Colorado, the SuperDitch, a collection of ditches, has been created by farmers in the Arkansas River valley to provide income for farmers and water for cities. In 2004, the City of Aurora, Colorado successfully pursued fallowing in the Arkansas Basin in the midst of a severe drought to provide about 7500 acre-feet for emergency supplies. In 2005, Colorado Springs joined with Aurora to extend the agreement for an additional year. The extension was used to refill depleted reservoirs with about 10,000 acre-feet of water.

[4] The 2004 agreement only allows for a maximum of 26,000 fallowed acres. A later additional emergency fallowing agreement increased this amount by an additional 13,000 acres in one year.

4 Crop Switching Summary

Crop switching has been proposed as a way to save large amounts of water in the West, including the Colorado River Basin. While in theory this technique is appealing as a way to save water, numerous studies and publications have shown that crop switching is difficult to implement because there are many complicated and potentially expensive issues to resolve. For a farmer, crop switching implies modifying much of what they depend upon to generate income.

4.1 Calls for Crop Switching Often Ignore Larger Economic and Market Forces

Large economic and market forces encourage farmers to produce many traditional, water-intensive crops. These crops have an entire production and risk management system built around them.

4.2 The Lower Basin Has More Crop Switching Opportunities

For crop switching to work, the new crop must offer lower water usage, relative to the old crop. Unfortunately, the consumptive-use difference between crops in the Upper Colorado River Basin is often relatively small, because the Upper Basin has lower evapotranspiration due to cooler temperatures and a shorter growing season. This decreases the crop-switching advantages in the Upper Basin. A few locations in the Upper Basin, such as the Uncompahgre and Grand Valleys in Colorado, do have climates that allow for many different crops. There are more crop-switching options in the Lower Basin because the climate there allows for greater crop selection, and because the longer growing season increases the water-use difference between high- and low-consumptive-use crops.

4.3 Farm Level Concerns

Soils, irrigation systems, farm equipment, labor and risk management instruments are all farm-level issues that must be surmounted in order to switch crops. These are discussed below.

a. Climate and Soils Constrain Crop Selection.

In the West, alternative crops must be able to survive, and even thrive in extreme conditions, including aridity, wind, hail, maximum and minimum temperatures, and other unusual weather. Compared to alfalfa and other forage crops, vegetables and fruits are only suitable for certain soils, and are generally less resilient to weather extremes. The risks from insect pests, crop diseases, and weeds are often tied to soils and climate, and with new crops these risks are not well understood.

b. Vegetables Generally Require Higher Water Quality Than Forage Crops.

With a switch to vegetables, either a new source of water may be necessary, or investments may be needed to improve the quality of the water being used.

c. Water-Delivery Methods May Need to Change.

To shift crops to orchards and vineyards, a farmer may need to invest in micro-irrigation. Micro-irrigation and sprinklers require clean water and a pressurized delivery system.

d. Crop Switching Can Reduce Drought Resiliency

Perennial tree and vine crops, unfortunately, require consistent irrigation and cannot be fallowed or reduced in acreage in times of drought like forages. Switching to these crops can thus reduce resiliency when a drought occurs. This can impact the individual farmer as well as entire basins if large transitions to these crops occur. This has been the case in California with the large-scale switch to highly profitable nut trees.

e. Farming is Very Specialized and New Knowledge May Be Necessary.

In many headwater streams, ranching is the predominant activity, with irrigation used to grow grass forages. Even if the climate allowed it, asking ranchers to transition to growing crops is extremely unlikely and would represent a dramatic shift in their agronomic knowledge. Acquiring the knowledge and skills to grow a new crop requires a significant investment. There needs to be an effective network, including extension services, to disperse and share knowledge on any new crop.

f. Significant On-Farm Investment May Be Needed for New Equipment and Inputs.

Ideally, with crop switching farm investments would be minimal. Especially compared to alfalfa and other forages, the most common crops in the Colorado River Basin, most crops require more fertilizers, herbicides, pesticides, and/or other inputs, thus raising farm operating costs.

g. Labor Needs May Change, Impacting Costs.

Most high-value crops like lettuce require intensive labor, unlike forage crops. Production of labor-intensive crops in some parts of the basin may not be competitive due to the lower cost of labor in countries like Mexico. On the other hand, transitioning from an existing, labor-intensive crop can reduce rural labor demand, depress rural wages, and threaten agricultural households and communities.

h. Financial Risk Management Mechanisms, Such as Insurance May Not Be Available.

The supporting bank will want to know that the farmer has the necessary knowledge to plant, harvest, and market a crop. The ability to store the crop before shipment, if needed, may be important. Knowledge of how markets might affect the final price is necessary, as are hedging mechanisms for that price.

i. Alfalfa, Often the Crop to Replace, Has Significant Benefits

Alfalfa consistently has the highest consumptive use of any crop in the basin. For this reason, it is often a target for replacement. By switching out of alfalfa, however, farmers forego significant benefits. Alfalfa is planted once and lasts for several years, thereby reducing annual input costs. Pesticides and herbicides are often not used. As a nitrogen-fixing legume, it can be an important crop in a rotation, and it does not require nitrogen fertilization. It is relatively easy to grow, and is robust to varying weather and climate conditions. It is drought-tolerant.

Because humans do not consume it, alfalfa is less susceptible to quality concerns, although these can certainly affect its market price. It can be readily stored and sold later when prices are high. It has a widely available and growing market, thanks in part to the emergence of a strong dairy sector in the

West. Until recently, prices have been high. In short, farmers know how to grow this crop, it is relatively low risk, and it provides decent, reliable returns. Any other crop can look risky by comparison.

It seems unlikely that unknown non-forage niche crops will replace alfalfa, at least in the short term. A better strategy might be to replace one forage (alfalfa) with another, less water intensive forage, such as forage sorghum. This approach would affect the overall forage market less by providing a substitute crop. Were large declines to occur in alfalfa production, surely alfalfa prices would rise, thus encouraging more alfalfa production.

4.4 Broad Scale, Off-Farm Issues

There are also significantly larger economic, political, and business factors that can limit a farmer's options of what to grow. Even though switching to low-water-use crops may conserve water, such a change may be economically unviable due to these off-farm issues.

a. Large Shifts in Output May Impact Prices, Farmers' Incomes and Other Agricultural Sectors

One proposal to shift a significant amount of acreage from alfalfa to fresh tomatoes in California would likely have a dramatic effect on prices. Processing facilities and a market for the new crop need to exist. The market for vegetables and high-value crops can also be much more volatile, with more market fluctuations in price than traditional crops.

b. Politics and International Competition are Significant Factors in Crop Selection

There is also a competitive disadvantage for U.S. growers for produce that can be grown less expensively in other countries. Many areas in the Colorado River Basin are well-suited economically for alfalfa and forage production, but cannot compete with the low-cost production of certain crops in other countries, thus encouraging continuation of current cropping patterns

c. Subsidies May Constrain Changes in Crop Production

Cotton, a crop with high consumptive water use, has been supported by federal subsidies. These subsidies encourage production and discourage switches to alternative crops.

d. An Entire Supporting Infrastructure Often Has to Be Built Around New Alternative Crops.

This new business infrastructure includes seed and fertilizer supplies, marketing and distribution networks, and even processing and storage facilities. Plus, processing a crop often requires a certain amount of crop to justify the investment in processing and storage facilities.

e. Water Law Disincentives

In most Western states, there are strong water law disincentives against switching crops to save water. The key disincentive is the loss of historical crop consumptive use when switching to a crop that uses less water. When selling a water right, an historical consumptive-use analysis, based on the actual crops grown, determines how much water can be transferred. Only this historical consumptive use can be sold, not the far larger decreed headgate diversion amount. This, unfortunately, provides a strong incentive for growing crops with large consumptive water use.

Colorado farmers know that alfalfa uses lots of water, and they believe that growing it will preserve their water rights and maximize their return in a future sale. If a farmer wanted to monetize the water savings from crop switching, the savings would need to legally quantified and transferred at the time of the switch, not later when lower consumptive use numbers would apply. Finally, a farmer's water rights are his or her most valuable asset, and selling these assets are often the only retirement plan the farmer has; this fact further encourages maximum use.

4.5 Case Studies

There are very few cases of switching crops to save water. The Walker River Basin in Wyoming is one case, although this example was funded by the federal government in an unusual experiment. There are many cases of crop switching encouraged by market forces. Avocados took decades to become a mainstream crop. Nuts, on the other hand, became a very large and valuable crop in California in about two decades. Both provide interesting lessons. Since the mid-1970s, growers in the Yuma area have switched from citrus, cotton and other crops into more sophisticated multi-cropping oriented around very profitable winter vegetables, saving about 250,000 acre-feet per year. Some of the Yuma savings also arise from irrigation efficiency improvements.

5 Irrigation Efficiency and Water Conservation Summary

Two related ideas, ***irrigation efficiency*** and ***water conservation***, can be used to obtain water from agriculture for other purposes. These concepts are related, because improving irrigation efficiency and improving water conservation can both lead to reductions in water use. The two terms as defined herein, however, deal with distinctly different kinds of reductions in water use. Each concept has different physical and legal ramifications, especially in terms of how they affect other uses and users. Both concepts can potentially provide water for municipal or environmental purposes from agriculture.

5.1 Key Definitions

Consumptive use is defined as liquid water that has been converted to water vapor*,* by either evaporation or plant transpiration. It is therefore no longer available for use. In some limited cases, water can also be considered "consumed" if liquid fresh water flows to a salty water body. This also makes it unavailable for crop and most human uses. It is still available for environmental purposes, however. Water that is diverted but not consumptively used becomes **return flows**, liquid water that returns either immediately to the stream as surface runoff, or as delayed groundwater. Return flows are heavily relied upon by downstream diverters in the West. In many basins in the West, the total diversions vastly exceed the total flows in the river, which provides strong evidence for how important return flows are.

Improving **irrigation efficiency** refers to *the act of saving* **non-consumptive-use water**, sometimes called **"saved water."** This might typically occur by reducing ditch conveyance losses, which would allow for smaller headgate diversions for the same volume of water reaching the field at the end of the ditch.

Water conservation, by contrast, is *the act of saving* **consumptive-use water.** Water conservation is further broken into two types. Savings from reducing non-productive consumptive use such as occurs by phreatophytes is called **'salvage water'** under Colorado law. It might have different names in other states. This water in most states is not legally transferrable and thus there is little incentive to reduce this use. In addition, the generation of salvage water can impact amenity values including mature trees on ditches. By contrast, **conserved consumptive use water** comes from reductions from crop consumptive use or ancillary consumptive use necessary to get water to crops such as evaporation from canals. This water is generally legally transferrable.

In general, greater quantities of **saved water** can be created than water saved from reducing **consumptive use**, in large part because in flood irrigation, the most common form, 50% of the diverted water is not consumed and becomes return flows. A farmer can generate significant saved water without affecting consumptive use, a key driver of crop yields. On the other hand, reducing conserved consumptive use leads to crop yield reductions and therefore has economic impacts. Reducing consumptive use affects fewer water users because this water was already used, and not available for reallocation via return flows.

5.2 Understanding Irrigation Efficiency

The term "**irrigation efficiency**" is most commonly defined as a percentage:

$$Irrigation\ Efficiency = \frac{Crop\ Consumptive\ Use}{Total\ Stream\ Diversions}$$

This definition leads to misunderstandings because in most engineering fields, efficiencies of less than 100% imply a loss or waste, such as wasted heat in energy applications. In water, however, the loss or "waste" is still liquid water that will ultimately be recycled as a return flow at some point in space and time. Return flows are highly valuable, and should not be considered "waste."

5.3 Critical Nature of Return Flows

Return flows provide water supplies for many downstream users and thus are important in many river basins in the West. Farms using flood irrigation are often only 50% efficient, meaning that 50% of their diversions return to the river for recycling. Because of recycling, "stacked" farms that rely on irrigation return flows can obtain high collective efficiencies, a feature sometimes known as the "basin approach." Sprinklers and drip can reach 80 to 90% efficiency with commensurate reductions in return flows.

A water mass balance, which is merely the application of the law of conservation of mass[5] to a suitably large geography and time period to account for all the consumed and non-consumed flows of water (both liquid and vapor), can help to understand how water is being used. Mass balances can indicate the importance of return flows, among other purposes.

There is a vigorous debate over whether return flows are good or bad — and implicitly, whether efficiency improvements (which almost always change return flows) are good or bad. The answer depends on the soil, runoff contaminants, if any, water temperatures, changes to the natural hydrograph, local geography, the location, and priorities of other diverters, and even the values of the observer. When return flows change, there are often winners and losers, including nature, which also influences the answers to this question.

[5] The law of conservation of mass says that matter can neither be created nor destroyed. It is a fundamental tool used in almost all engineering and physics studies.

5.4 On-farm vs. District-Wide Efforts to Improve Efficiency

Irrigation efficiency improvements can be broken into on-farm and district-wide efforts. On-farm efforts include increasing the delivery efficiency from headgate to field by lining or piping canals and increasing the field application efficiency, defined as the amount of water consumed by crops divided by the total amount applied to the field. Field application efficiencies can be increased by laser leveling, tailwater recovery (capturing water at the end of the field and reusing it), and installing sprinklers, or drip and other methods. Irrigation scheduling can increase efficiency by only applying water when it is needed, which can reduce unnecessary soil evaporation.

District-wide efficiency measures include similar actions to on-farm measures but done on a larger scale, such as canal lining. With large systems involving tens of miles of canals and many hours of water travel times, keeping canals full, especially near the end of the canal after many laterals have withdrawn water, has historically been challenging. Operators would often rather spill water from the tail end of the canal than run short, which has meant that the river segment between the headgate and the tail end of the canal has had less water than it might. Computerized canal check structures – small movable, vertical dam-like structures within a canal -- can keep canals full when they have less water, while reducing spills at the end of the canal. Small operational reservoirs, often near the end of a lengthy canal, can capture and allow reuse in the difficult-to-serve lower canal reaches.

5.5 Co-Benefits of Increasing Irrigation Efficiency

Co-benefits of irrigation efficiency improvements that reduce diversions are important. These benefits include increased water quality due to reductions in saline or chemical-laden farm runoff, less groundwater pumping in groundwater dependent systems, and higher reliability of diversions due to the need for less carriage water. Increased efficiencies can increase productivity, yields, and economic gain. In the 21st century these improvements can be as important as considerations of total water quantity, which has heretofore dominated water supply conversations.

Many irrigation systems are decades old, and in need of infrastructure maintenance and improvements. Efficiency improvements generally provide modern automated management, which reduces labor and increases flexibility. This is another co-benefit.

5.6 Increased Consumptive Use From Improved Irrigation Efficiency

Improving irrigation efficiency often has the paradoxical effect of increasing consumptive use. This has been known for many years and proven in many field-level and modeling studies, yet it is frequently misunderstood by the public. Technologies that improve field application efficiency apply water more uniformly in space, and often remove a time and labor constraint associated with flood irrigation. By flipping a switch, crops on sprinklers or drip can receive water whenever needed, not just on a set schedule dictated by canal capacity and/or labor. Many farm operations are constrained by delivery capacities (i.e., are “water-short”); improvements allow more diverted water to be applied to the crop rather than lost as a return flow. In these water short systems, yields and consumptive use can go up because more of the diverted water makes it to the crops that were previously unintentionally deficit irrigated. Increased consumptive use thus means fewer return flows for use by downstream diverters.

Improved irrigation efficiency is often portrayed as leaving more water in the stream, downstream of the headgate of the improver. While this is one outcome, others are possible. The efficiency improvement can lead to the same diversions, more consumptive use, and less return flow as described above. Under another scenario, if the saved water is not diverted, under prior appropriation the next-in-line diverter may be upstream, not downstream. In this case, there will be a reduction in flow from the next-in-line diverter's headgate down to the headgate of the diverter installing the efficiency improvement. This is a paradoxical outcome that is rarely mentioned, and one that is not often envisioned by the promoters of irrigation efficiency.

5.7 Water Conservation Opportunities

Water conservation measures include reducing non-beneficial consumptive use, reducing crop and non-crop transpiration, reducing runoff into saline water bodies, and utilizing rainfall more effectively. Several studies suggest that savings from reducing non-beneficial evaporation from soil can be from 20 to 40%. Reducing other forms of non-beneficial evaporation such as phreatophyte removal may harm amenity values associated with trees and other vegetation. Reducing crop transpiration will reduce yields. Reducing weeds can provide additional water.

Reducing runoff to saline water bodies is a different kind of consumptive use reduction. Most consumptive use occurs when liquid water is evaporated or transpired to water vapor. This method, however, involves stopping fresh liquid water from being converted to unusable saline water. In arid areas throughout the world, saline water bodies can support important biological activities and thus this kind of consumptive use reduction impairs the environmental values of the saline body. Mono Lake, Owens Lake and the Salton Sea are three examples in the Western United States and there are many elsewhere around the world. There is little opportunity for more effective rainfall utilization in the West as rainfall provides only a small portion of crop water needs in many of the most important irrigation areas.

Some projects that have focused on salinity control such as canal lining efforts are also irrigation efficiency projects. While these improvements can lead to higher consumptive use, they also improve the quality of agricultural runoff and hence enhance stream water quality for downstream users.

If changes in return flows are a concern, one solution is to make efficiency improvements at the end of a river first, and then work up-river. This approach minimizes return flow impacts to downstream diverters, while potentially improving instream flows and water quality downstream of the improvements, provided that saved flows can be "shepherded" downstream rather than being taken by upstream next-in-line diverters.

5.8 Case Studies

There are many cases of irrigation efficiency improvement projects in the West. The Metropolitan Water District on Southern California has an on-going program at the Imperial Irrigation District to save approximately 100,000 acre-feet of water every year. The Yuma area in Arizona has used about 250,000 less acre-feet per year, in part due to different crops and in part due to sprinklers, high flow turnouts, laser leveling and other efficiency methods. In Colorado, one large irrigation district near Grand Junction saved nearly 40,000 acre-feet per year in some years by lining canals, automating gates, installing check structures, and using a reservoir near the end of a long canal with no loss of agricultural output.