Water Shortages and Drought: From Challenges to Solutions

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The U.S. society for irrigation and drainage professionals

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Preface

The papers included in these Proceedings were presented during the **USCID Water Management Conference**, held May 17-20, 2016, in San Diego, California. The Theme of the Conference was ***Water Shortages and Drought: From Challenges to Solutions***.

The Western United States is facing unprecedented and prolonged drought conditions. Even without near-record high temperature and low rainfall, we have more hardened water demands in the 21st century than we experienced in the last century. Water supplies appear to be less reliable, there is a growing regulatory focus on sustainable groundwater management, and there are very real concerns about fundamental changes in our hydrology and watersheds.

Throughout the West, water managers at the local, regional, state and national levels are undertaking major changes in how we manage our connected surface and ground water supplies. This promises to have significant impacts on food production, urban water supplies and the economy. There is growing public focus on long-term sustainability for our economy, our food supplies and environment. The "triple bottom line" theoretical approach to sustainability will be a difficult and rocky path.

Agriculture has never faced the challenges we face today. During the past decade, new water management institutions have been created in many regions and in every state, each developed to respond to their own water challenges and legal/ institutional frameworks. Modern water managers are embracing the concept of resilience: the need to be as flexible as possible in the face of increasing uncertainty. This Conference focused on the pressures of water shortages (both short-term and long-term), and how we are rising to the challenges by developing innovative solutions.

The authors of papers presented in these Proceedings are a mix of professionals from federal, state and local government agencies; water and irrigation districts; the private sector; and academia.

USCID and the Conference Co-Chairs express gratitude to the authors, session moderators and participants for their contributions.

Steve Macaulay
Winters, California

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Conference Co-Chairs

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EVOLVING CAPITAL IMPROVEMENT PROGRAM TO MEET FUTURE WATER DEMANDS

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ABSTRACT

In 2011, the Solano Irrigation District (District) contracted with Davids Engineering (Consultant) to perform the first phase of a water balance study. The first phase water balance was a broad overview of the District's current, typical demands and available annual allocation. The purpose of the first phase water balance was to determine if water shortages were likely to occur in the future. Since the results of the first phase water balance indicated that future water shortages were possible, the District had the Consultant begin work on the second phase water balance study in 2014, while the District worked concurrently on a Strategic Plan (Plan). The second phase projected future water usage and cropping patterns, addressed changes to on-farm irrigation efficiency, accounted for the District's existing water contracts with other agencies, and included possible future climate changes. The results of the second phase water balance determined that the District, on average and based on a probable cropping pattern change and existing delivery efficiencies, will have a greater demand than supply. As a result of the water balance findings and vision established by the Plan, the District modified its Capital Improvement Program (CIP) to curtail facility rehabilitation projects and begin the implementation of projects designed to recover water, reduce losses, or produce water from alternative sources required to supply safe and reliable water to District customers. The modified CIP is aggressive and expensive, but provides the District with multiple opportunities to receive grant funding from both the U.S. Bureau of Reclamation (USBR) and the State of California for project cost sharing. Currently, the District is working on projects to automate our largest canal, install a recovery structure to capture approximately 12,000 acre-feet (AF) of water annually that typically leaves the District, and automate several deepwells to reduce unnecessary pumping and approximately 800 AF of spill. Future projects include the automation of the District's second largest canal, additional recovery structures, and regulating reservoirs.

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INTRODUCTION

The District was formed in 1948 to provide agricultural water to growers within Solano County. Since its formation, the District's client portfolio has increased from solely delivering agricultural irrigation water to providing municipal water and non-potable landscape irrigation water. With such a diverse range of customers, from commercial agricultural operations, to city and commercial landscaping, to drinking water, the District found it necessary to develop a Plan[5] for the continued delivery of 'safe and reliable water'.

Over the course of the District's history, since the first water delivery in 1959, the District has been able to deliver 100% of grower's demands while sustaining ground water supplies, with the exception of one year, in 1992. Through volumetric accounting for water purchased by the District and water sold to the District's customers and by monitoring groundwater levels, District staff had a general idea that District supply and demand was sustainable. In recent years however, several events, such as climate change, cropping patterns, and water contracts, have created a scenario in which the District may not have sufficient water supplies to meet future water demands.

The reliability of surface water and ground water supplies are becoming increasingly important issues for water purveyors. The necessity of balancing water supply and water demand has been thrust to the forefront by California's recent drought. In anticipation of these changes, the District has been making a proactive effort to audit and maintain surface and groundwater supplies for the past five years. The District's first step, as outlined in the District's Plan, was to develop a detailed water balance. The District contracted with Davids Engineering (Davis, California) in 2011 to begin the first phase of the water balance study (Study) comparing water supplies and demands. The results of the first phase Study indicated a possible shortage in meeting future water demands. Due to the first phase Study results, the District engaged Davids Engineering for the second phase Study to complete a full water balance tracking all inflows and outflows. The findings of the second phase Study, completed in July, 2015, were of great importance as the results not only achieved the highest priority action of the District's Plan, but also contained invaluable information required for defining the District's water allocation policy and capital improvement program, also key tenets of the Plan.

The concept and recognition of the need to develop a policy to allocate water within and amongst the District's service area became apparent in 2012. With Statewide water shortages beginning in 2012 and the inability to secure reliable long-term water supplies, many permanent crop growers (namely Almond and Walnut producers) were fleeing the Central Valley and searching for areas to relocate to with secure/reliable water supplies. The Solano Irrigation District was targeted as a highly viable location based on the tremendous supply reliability since 1959. As such, the District began experiencing a large influx of permanent crops beginning in 2013 that continues to date. District staff recognized the potential for future water shortages with large areas of traditionally low-water demand crops to crops with an increased water demand utilizing highly efficient

[5] http://sidwater.org/DocumentCenter/View/791

irrigation methodologies yielding virtually no surface water run-off. A Water Allocation Policy (WAP) needed to manage potential future shortages in surface water supply that could lead to increased groundwater pumping to meet the additional demands. To address this potential water shortage issue, District staff developed a WAP, which was completed in November, 2015, and implemented for the 2016 irrigation season. The WAP establishes volumetric limits set each year based on water supply to the water available to each grower based on acreage of the property being irrigated. Additionally, the (WAP), which was the second highest priority identified by the District's Plan, will ensure the equitable and reliable delivery of water.

While the WAP, as discussed later in this paper, will uniformly distribute our current water supplies, the Study concluded that future water demands have a high probability of exceeding current water supplies. Since the District is not able to curtail future demands, the District is faced with the challenge of increasing future supplies and improving the delivery efficiency of existing supplies. Prior to the Study, the District focused most of the capital improvement funds towards the replacement of aging infrastructure. Most of the former CIP projects replaced failing pipelines with new PVC pipelines, a type of project which improves level of service and saves some water but does not save a measurable volume of water. District staff recognized that in order to begin developing future supplies, a shift in the concept and approach of the Capital Improvement Plan prioritization was fundamental. As such, the District transformed the CIP, transitioning from facility replacement projects to water conserving projects. The District placed a great deal of importance on projects that incorporate conjunctive use of surface and groundwater supplies, recover water, or prevent unnecessary distribution system losses, and projects that have potential benefits for increasing on-farm water use efficiencies.

The transformation the District has made over the past five years will be invaluable in meeting future water demands but has not been without trial and tribulation. In retrospect, some of the processes undertaken could have been performed in a better, sequential order. In some cases, the District underestimated the amount of staff time, resources, and duration required for the processes to be completed. As with any great organization, the District does not view these shortfalls as such, rather as learning opportunities for future projects as well as for other agencies that desire to perform a similar process for ensuring future water demands are met. This paper includes a brief background of the District, describes the water balance study, the water allocation policy and the lessons learned.

BACKGROUND

<u>District Overview</u>

The District is located in Solano County, midway between San Francisco and Sacramento. Figure 1 is a Location Map for the District to provide some context for the general location within the State and a map of the geographic location of the District within Solano County.

The District was organized in 1948 under the provisions of the California Irrigation District Law for the purpose of contracting surface water supplies from the USBR's Solano Project. Upon formation of the District, the District and Solano County made a substantial effort to obtain authorization and congressional funding for the construction of Monticello Dam and Lake Berryessa, the Putah Diversion Dam, the Putah South Canal (PSC) and the District's water distribution system. The Solano Project was authorized by the Secretary of the Interior on November 11, 1948 under the terms of the Reclamation Project Act of 1939. The Solano County Flood Control and Water Conservation District entered into a contract with the USBR on behalf of the Solano Project Member Units. The Solano County Flood Control and Water Conservation District was dissolved subsequently and the Solano County Water Agency (SCWA) now represents the Solano Project Member Units.

The Solano Project was completed approximately six years after construction began, and the first Solano Project water was delivered in the spring of 1959. The Solano Project consists of Lake Berryessa, Monticello Dam, Putah Diversion Dam on Putah Creek, PSC, Terminal Reservoir, and the conveyance facilities that deliver surface water to the member units. By the spring of 1963 all lands within the District had water available. The average annual deliveries from the Solano Project are approximately 200,000 AF, of which the District receives 141,000 AF.

The District's average annual water supply is approximately 155,000 AF, including groundwater resources, recovery pumping of drainage water and supplies for municipal and industrial users. Approximately 147,000 AF/year is delivered to farms and 8,000 AF/year is delivered to municipal and industrial users. Currently there are 1,834 agricultural water users and 1,200 urban connections. Irrigation methods include furrow, flood, sprinklers, drip, and micro-sprinkler irrigation systems. Major crops include tomatoes, alfalfa, grapes, wheat, corn, walnuts, almonds, nursery stock and pasture. The total acres served within the 70,773 acre district are approximately 63,393 irrigable acres. Domestic water customers include agreements with the cities of Fairfield and Vacaville, businesses, and District partnership with Suisun-Solano Water Authority (SSWA).

The primary conveyance facility for the Solano Project is the PSC, which is concrete lined and 33 miles in length. The PSC distributes water through sixty (60) lateral canals and turnouts, of which the Vaughn Canal is the largest and diverts the greatest amount of water. The District's distribution system consists of gravity diversions from the PSC and pumped diversions to the service areas. The distribution system consists of approximately 95 miles of open canals, six miles of lined canals, and 77 miles of pipeline. The District operates four drainage recovery dams and five reservoirs of which 114,921 square feet are lined and 83,521 square-feet are unlined. In addition there are several tail-water recovery systems, 55 recovery pumps, and a conjunctive use program in place to utilize 23 District-owned deep groundwater wells to supplement water demands when needed.

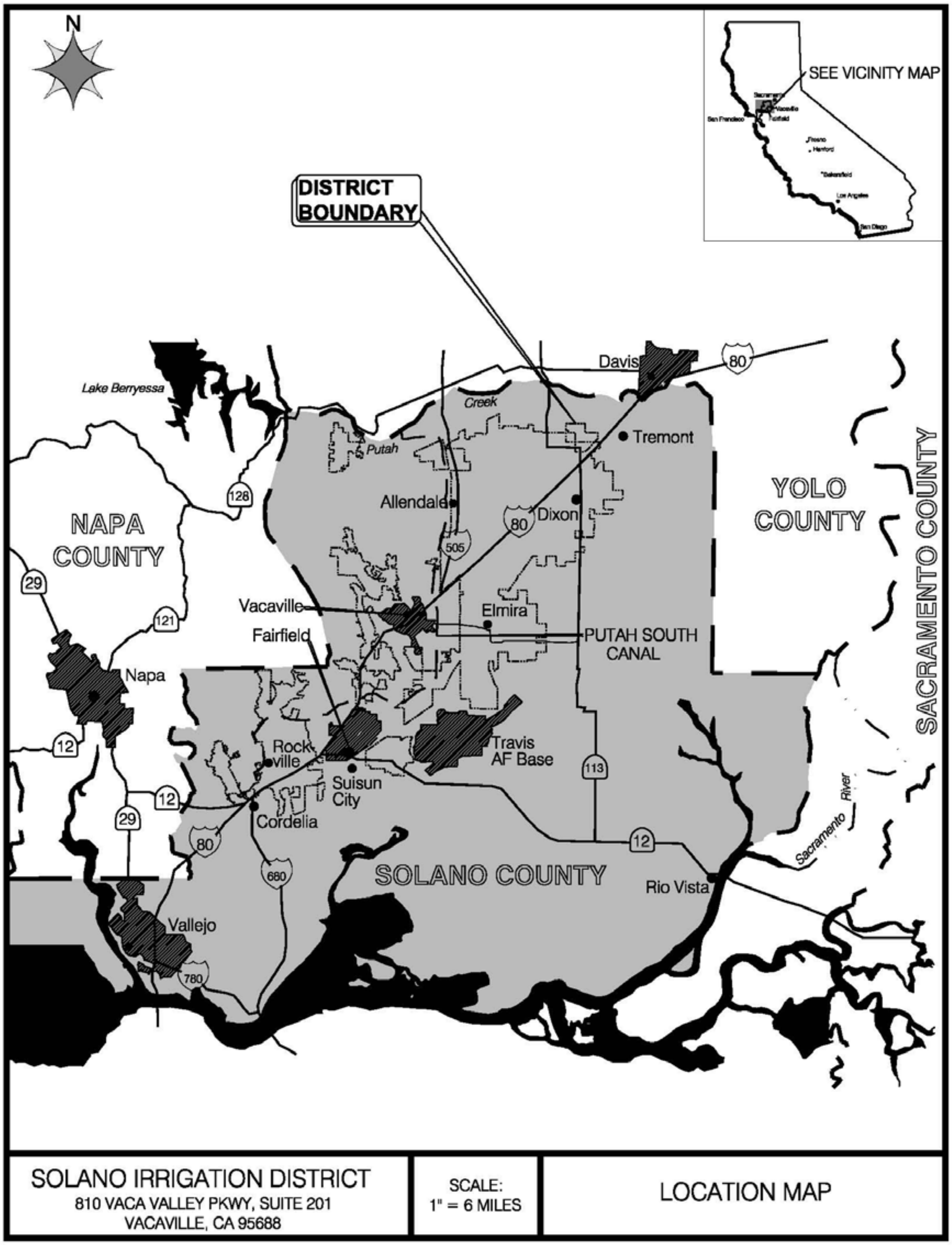

Figure 1. Location Map

Former Capital Improvement Programs

In August, 1985, Summers Engineering completed a report entitled *A Plan for the Improvement of the Irrigation Distribution Works*. The report presented a large collection of projects and their estimated cost for the rehabilitation of the District's facilities. The need was driven by the increasing maintenance and operation costs of a system that had been in operation for over 25 years. It was recommended to immediately implement the proposed plan (or one like it) and have it completed within a ten-year time frame. The original plan had consisted of 133 projects for an estimated cost of $17.74 million (1985 dollars).

The plan was updated in 1993 and adopted the U. S. Bureau of Reclamation's (USBR) term, Rehabilitation and Betterment Program (R&B). Even though the District had completed many projects form the original plan, the need for a District-wide implementation program increased due to the aging of the distribution system. The update revised the original project list and included additional projects. These new projects were based primarily on the increasing maintenance and downtime of the aging distribution systems which at that time were almost 35 years old. The updated plan had 193 projects for an estimated cost of $29.89 million (1992 dollars). The District elected to utilize funding from an annual property tax assessment transfer and Monticello Power Plant revenues to initiate the improvements.

By 2011, the distribution system was over 50 years old but still provided growers with a dependable water source. The District had expanded the updated 1993 plan and completed over 279 projects, not included the many small improvements, completed as part of annual recurring budgets, at a cost of $32.69 million over the previous 17 years. The list of completed projects included concrete lining of 4.52 miles of earthen canal, replacing 28 miles of pipeline ranging in size from 12" to 54", and drilling six replacement deepwells.

The 2011 CIP was the most recent five-year plan developed by staff. The plan forecast contained 19 categories with replacement of 105 miles of pipeline, installation of 90 SCADA sites, construction of 281 headworks gates, drilling nine additional deepwells, concrete lining 87 miles of canal, construction of two regulating reservoirs, reconstruction of 19 pumping plants and various other projects for a projected cost of $240.9 million (2011 dollars).

Insight for a Water Balance Study

The District has several old and complex water transfer agreements with cities that pushed major water transfers toward the end of the agreements or ramped up over time. Most notably, a large lump sum entitlement transfer to the City of Fairfield. Couple the future water transfers to cities with the history that SID has always seemed to have enough water available to meet its demands (with the exception of 1992 during the drought), one could see why a complacent attitude toward water supply existed.

Therefore, past water supply studies were relatively simple using actual water delivered compared to previous cropping patterns. The studies met the need at the time.

With a major water transfer to Fairfield approaching in 2024, and changing cropping patterns in the State, the District needed a solid foundation to take a strategic position and address potential risks of demands exceeding supply. SID needed a comprehensive water balance.

WATER BALANCE

A water balance of SID was developed to assess the probability and magnitude of potential future supply shortages, to guide development of surface water allocation and land annexation policies, to assess implications to groundwater management and to support SID's ongoing system optimization review. Additionally, the water balance supports the recent and future updates of the District's Water Management Plan, which is required by the United States Bureau of Reclamation and the State of California, and other SID water management initiatives and processes. This section briefly describes the data collection, data processing, methodology, results and recommendations.

Data Collection

Development of a multi-year water balance is necessary to evaluate water management impacts of surface water supply variability, precipitation variability, and other changes in the hydrology of SID and its surrounding area over time. Specifically, a multi-year water balance that includes both dry and normal years is essential to evaluate and plan for water supply shortages and develop policies in response to shortages. For the District's Study, the years from 1991-2014 were selected for several reasons. First, these years should cover enough irrigation seasons to evaluate the variability in water supply, demand and climate. Second, 2014 was the most recently completed irrigation season from which a full irrigation years' worth of data could be used. Lastly, 1991 was the first year the District began maintaining significant enough records that information for most parameters was available.

Irrigated Acres. Irrigated acres and crop type for each turnout are obtained the 'Crop Declaration Form' provided to the District annually by growers.

Cropping Patterns. Crops listed in historical District crop reports were assigned to one of five primary crop groups. Annual acreages by crop type for the 1991 to 2014 study period are shown graphically in Figure 2. Note that the District crop survey data were not available for 2004. As a result, 2004 acreages by crop group were estimated as the average of the 2003 and 2005 acreages. Agricultural land use classes that are not irrigated, i.e. dry farming are "Not Assigned" (NA) to a crop group. Second crops are included with the crop group of first crop. For example, the District estimates that about 20 percent of the grain crop area is planted to a second crop.

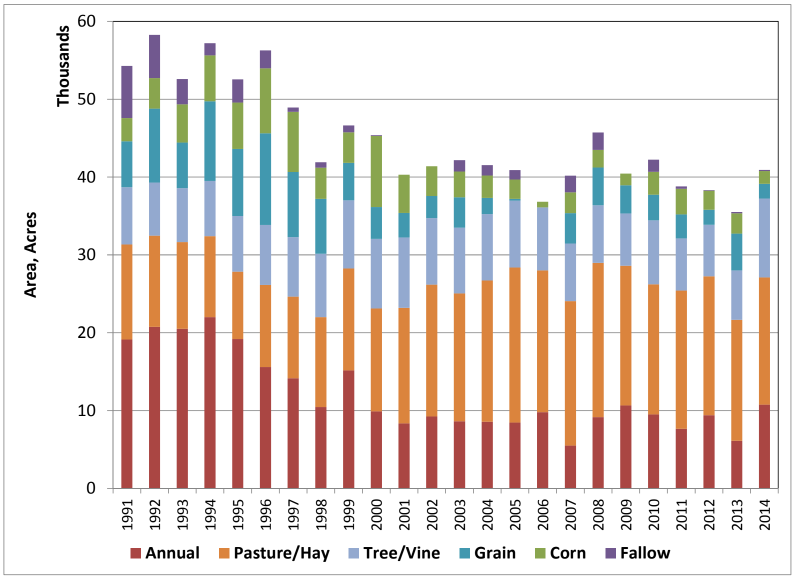

Figure 2. SID 1991 to 2014 Cropping by Crop Group

Applied Water. All District agricultural irrigation headworks, turnouts, and spills are measured using either volumetric delivery readings or flow rate readings for a specific duration of time. Since the Study required the actual volume of water being applied to the irrigated lands, the delivery records for each turnout had to be summed for each year. The applied water volume does not reflect the total diversion from the PSC into the District's distribution system. The total diversion volumes from the PSC include water lost to seepage, water lost to evaporation, water lost to spillage, and municipal and industrial water.

Agreements with Cities. Development results in a loss of agricultural land. In an effort to secure future revenues that are lost as agricultural land develops, the District entered into water agreements with the City of Vacaville and the City of Fairfield. The first agreement the District entered into was with the City of Fairfield in 1974. The 1974 Fairfield Agreement outlined the transfer of 6,000 AF of District entitlements to the City of Fairfield. The 1974 Fairfield Agreement was amended in 2002 to increase the original entitlement transfer. Per the terms of the amended 1974 Fairfield Agreement, the District is required to transfer 16,018.50 AF of entitlement to the City of Fairfield by the year 2024.

The District also entered into a Master Water Agreement with City of Vacaville in 1995, outlining a contractual volume of water the District will make available to the City that increases to 10,500 AF in 2040.

Data Processing

The objective of the Phase 1 Study was to quantify historical and current agricultural water demands. Agricultural water demands were quantified using a daily root zone water balance model to estimate the portion of total crop evapotranspiration resulting from applied irrigation water (ET_{aw}) over time (1991 to 2010, later extended to 2014) on the basis of cropping, soil characteristics, and weather (evaporative demand and precipitation). The primary driver of agricultural water demand is total crop evapotranspiration (ET), which was quantified based on a remote sensing analysis of actual ET conducted for the 2007 growing season. Crop coefficients were developed based on the remote sensing analysis for the individual crop groups and applied in the remaining years to estimate total crop ET over time.

The Phase 2 Study was developed to assess the probability and magnitude of potential future supply shortages, to guide development of surface water allocation and land annexation policies, to assess implications to groundwater management and to support the District's system optimization review.

<u>Determining Actual Evapotranspiration.</u> Actual crop coefficients were developed for major crop types within the District based on analysis of actual evapotranspiration (ET_a) using remote sensing for the 2007 crop season using the Surface Energy Balance Algorithm for Land (SEBAL®). Substantial variability in seasonal ET_a was observed within each general crop type, suggesting that growing conditions among fields differ greatly. Thus, future changes in cropping intensity within the District could result in changes in average water use by crop and corresponding agricultural water demands.

<u>Methodology</u>

By definition, a water balance accounts for all water entering and leaving a 3-dimensional space over a defined period of time, as well as any change in storage. For a water balance to yield meaningful results, its spatial and temporal boundaries must be clearly and strategically defined, and all flows across the defined boundaries and any changes in water storage within the boundaries during the analysis period must be accounted for. This generally includes surface water and groundwater supplies, rainfall, and exchanges with the underlying groundwater system via pumping and deep percolation.

In accordance to the principle of conservation of mass, the sum of the inflows and outflows plus any change in storage for each accounting center must be zero in each time step. The water balance was based on the following general mass balance equation:

$$(\text{Sum of inflows}) - (\text{sum of outflows}) \pm (\text{sum of changes in storage}) = 0$$

<u>Define boundaries.</u> The first step in performing the Study analysis was to develop a Study structure. Study structures are defined by accounting centers, which represent different geographic subdivisions of the Study domain, and flow paths that represent the movement of water between the accounting centers. For the District, a water balance structure with three accounting centers and their associated flow paths was developed (Figure 3). Next, each accounting center in the water balance was defined by establishing its upper, lower, and horizontal boundaries and selecting the flow path to be calculated as the closure term, as listed in Table 1 and described in greater detail below.

Table 1. SID Water Balance Accounting Centers and Boundaries

Accounting Center	Upper Boundary	Lower Boundary	Horizontal Boundary	Closure Term
SID Distribution Canals	Canal water surface	Canal wetted perimeter	All points of inflow and outflow including diversions, deliveries and spills	Farm Deliveries
Irrigated Lands	Crop canopy	Bottom of root zone	All points of inflow and outflow including deliveries and tailwater discharge points	Deep Percolation of Applied Water
Drainage System	Water surface	Drain wetted perimeter	All inflows, spills and discharge points past the District boundary	Drainwater Outflow

Once the Study structure and spatial boundaries were defined for each accounting center, the temporal boundaries of the Study are established. The water balance was completed for the full year, but excludes flows in streams and drains that result from precipitation that occurs outside the irrigation season. By excluding these flows, the impacts of irrigation on hydrology within the District were isolated while simultaneously the effect of winter precipitation on soil water content is included.

Development of a Water Balance Diagram. The development of a Study diagram is important for two reasons: 1. The diagram helps to visualize all the flow paths and accounting centers, making it easier to model the system, and 2. Once all flow paths and accounting centers have been established, the diagram acts as an audit device to make sure that all variables are included in the water balance calculations. The interaction between the three accounting centers identified, the atmosphere, and the earth resulted in a multitude of flow paths as shown in Figure 3.

Not all variables of the diagram were known or measured by the District. In order for the conservation of mass equation to equal zero, discrepancies between the inflow and outflow must be accounted for. As shown on the diagram, three closure flow paths were developed to account for the discrepancies. The farm deliveries flow path is a closure for the District's Distribution Canals accounting center and accounts for inaccuracies in flow measurement within the distribution system, errors in evaporation volumes, and for water lost to seepage, a volume that is not measured. The second closure flow path is deep percolation of applied water. The deep percolation of applied water is not a flow measured by the District and accounts for inaccuracies of the inflow and outflow and for the change in storage of the groundwater system. The last flow path, drainwater outflow, accounts for any discrepancies with the drainage system by either increasing or decreasing the volume of water lost from the system.

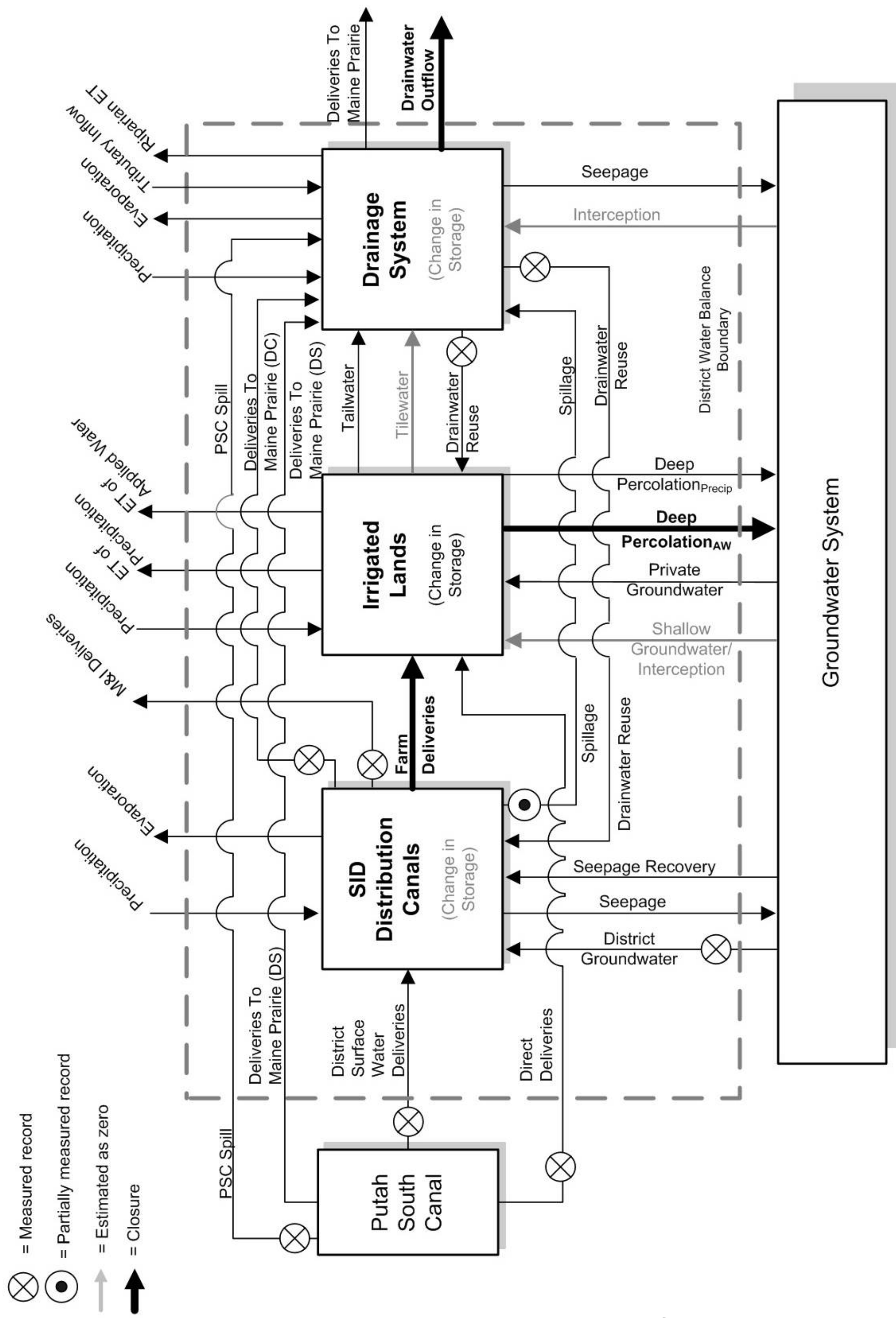

Figure 3. SID Water Balance Structure[6].

[6] Change in storage only included if significant.

Results

After quantifying water supplies, uses, and estimated losses, a water balance was applied to estimate the closure term for each accounting center. The water balance follows the water from lateral heads on the PSC, through the District laterals and the irrigated lands, and finally to the drainage system. Each accounting center is solved sequentially and iteratively so that the resulting individual accounting center balances are a reasonable reconciliation of the available data. Accounting centers are then combined to assess the overall District water balance.

Irrigation Efficiency. For the District's Distribution Canals, delivery efficiency was computed as the ratio of the Farm Deliveries to the sum of District Surface Water Deliveries from the Putah South Canal (into SID lateral headings), District Groundwater, Drainwater Reuse and Seepage Recovery. This performance indicator varied from 82 percent to 91 percent and averaged 87 percent over the 1991 through 2014 period for the months representing the irrigation season. The average value was used to represent existing system efficiency.

A Consumptive Use Fraction (CUF) was calculated for the Irrigated Lands accounting center as the ratio of evapotranspiration of applied water (ETaw) to the sum of farm deliveries, direct deliveries, private pumping and drainwater reuse. The CUF essentially represents the efficiency of on-farm water application. The CUF varied from 59 to 77 percent, and averaged 69 percent from 2004 through 2014. This period within the full 1991 through 2014 water balance period is regarded as being most the most reliable indicator of existing on-farm efficiency. For purposes of the Assessment, existing on-farm efficiency was assumed to be 70 percent.

Long Term Demand. The District developed seven scenarios to represent a range in future water demands to be used in evaluating future water supply shortages. Each scenario is formed by a unique combination of assumptions regarding future cropping patterns, different possible future cropping patterns, on-farm and SID distribution system efficiencies, permanent crop water use intensity, climate change, and urban water supply obligations. The different sets of assumptions defining the scenarios are summarized in Table 2.

All scenarios assume that SID's future urban water supply obligations will remain as they presently are under existing water supply contracts, except that Scenario 4 is also evaluated assuming that urban demands increase in 2024 to the quantities provided for in existing contracts.

The demand projections for all scenarios are based on historical weather conditions for 1970 through 2014, reflecting the global assumption that future climate conditions will be like recent historical conditions. The exception is that under Scenarios 5 and 6, demands are factored up according to published information to reflect the effects of climate change on crop ET.

Table 2. Future Water Demand Scenario Assumptions Summary

Scenario	Assumed Conditions				
	Cropping Pattern	Efficiency		Actual ET_{aw} Of Permanent Crops, Inches	Climate Change
		On-Farm	System		
1	Current	70%	87%	23.2 (Historical Average)	No
2	Current	70%	92%	23.2 (Historical Average)	No
3	Increased	78%	87%	27.2 (Historical 75th Percentile)	No
4	Increased	78%	92%	27.2 (Historical 75th Percentile)	No
5	Increased	78%	92%	27.2 (Historical 75th Percentile)	Low
6	Increased	78%	92%	27.2 (Historical 75th Percentile)	High
4 (2024) [7]	Increased	78%	92%	27.2 (Historical 75th Percentile)	No

Conclusions

The results of the Study were influential in taking all the pieces of information the District had and putting the puzzle together to provide the District with a landscape of the future. Since the District does not actively measure distribution system seepage, tailwater outflows to MPWD, or private groundwater pumping, the study did involve some sources of uncertainty.

The future demand scenarios that were developed for the Study represent a plausible range of possible future conditions, reflecting possible changes in irrigated area and cropping patterns, intensity of permanent crop water use, on-farm and system efficiency and climate. For all scenarios except Scenario 2, which is considered to be an unlikely future condition, frequent and appreciable shortages of surface water are forecast to occur given the District's current urban water supply obligations, as shown in Table 3. With the existing city contracts, these obligations increase in 2024 and will result in commensurate increases in future water supply shortages. Under the most challenging future conditions when urban supply obligations increase (Scenario 4 (2024)), District agricultural customers are forecast to experience water supply shortages 96 percent of the time, with maximum shortages of up to 60,000 AF, or 28 percent of total demand (agricultural and urban), in any given year.

These results are based on the assumption that the District and landowners within the District will continue to pump groundwater at recent historical levels (approximately 9,000 AF per year). Actual shortages would be less to the extent that the District and/or landowners pump additional groundwater or water demands are reduced, or some combination of the two. Whether sufficient additional groundwater could be developed sustainably remains a question.

[7] Scenario 4 (2024) has Urban Demand increased from existing quantities to the quantities provided for beginning in 2024 according to existing contracts.

Table 3. Summary of Water Shortages Forecasted Scenarios

Scenario	Ag Demand (AF)	Surface Water Supply (AF)	Supply Minus Demand (AF)	Urban Demand (AF)	Supply Minus Ag + Urban Demand	Average Groundwater Supply (AF)	Total of all Supplies and Demands (AF)
1	138,333	141,000	2,667	18,976	-16,310	9,000	-7,310
2	130,815	141,000	10,185	18,976	-8,792	9,000	208
3	150,497	141,000	-9,497	18,976	-28,474	9,000	-19,474
4	142,318	141,000	-1,318	18,976	-20,294	9,000	-11,294
4 (2024)	142,318	141,000	-1,318	34,929	-36,247	9,000	-27,247
5	144,453	141,000	-3,453	18,976	-22,429	9,000	-13,429
6	147,157	141,000	-6,157	18,976	-25,133	9,000	-16,133

The results of this analysis may not be immediately intuitive because District has never experienced a water shortage in its 56 years of operation. This apparent discrepancy is explained primarily by the assumption that the future conditions used to describe the various scenarios presently exist. In reality, the District is evolving toward these future conditions. Thus, while future shortages are likely to occur, exactly when they will begin is uncertain depending on District actions and the rate at which on-farm practices and climate occur.

Recommendations. Upon completion of the Study, several recommendations were developed. The recommendations included changes in District practices and record keeping needed to minimize uncertainties in future studies. The improvements include the following recommendations.

1. Tracking of cropped and irrigated area by instituting procedures to track all irrigated area including area that is not using District surface water supply. The District should also track changes in on-farm conditions to provide a firm basis for determining the crop water use and anticipating changes in water demands (as well as in customer service preferences).

2. The District should develop an integrated data storage and management system to enable regular water balance computations to better support water management planning and technical analyses.

3. Enhanced data quality control and reporting procedures should be implemented to develop high quality data to track the District’s cropping and water use, support regular agricultural water management planning and inform groundwater management planning.

4. Take measures to more accurately quantify groundwater pumping within the District, not only for District groundwater wells, but also private groundwater wells.

5. Do not increase or enter into any additional urban water agreements.

6. Develop and implement a policy for allocating available surface water supplies. A wide variety of options exist for doing this.

WATER ALLOCATION POLICY

In response to the changes occurring within the District, staff began developing a Water Allocation Policy (Policy) in 2013. The Policy was identified as the second highest priority in the District's. The specific strategy (§1.2 – Water Supply) was to maximize the beneficial use of all of SID's water by developing guidelines and management strategies allowing the District to administer a variety of programs/initiatives during wet, normal, drought and prolonged drought years. One of the objectives listed within the aforementioned strategy statement was to develop a Water Allocation Plan for fair and equitable distribution of available supply including varying levels of implementation based on supply conditions, inclusive of an internal drought contingency plan/policy.

Development Process

The development of the Policy was a multi-year process. Staff with numerous hours of input and collaboration from key agricultural stakeholders and the Board of Directors carefully developed the Policy.

Board Subcommittee. The District Board identified a two member Board subcommittee, designed to assist District staff with the Policy development.

Grower Participation. District staff invited 12 growers to meet regularly to discuss their concerns towards limitations the Policy may produce for local farming operations and for them to bring forward creative solutions for the new Policy.

Policy Guidelines

When the District was formed in 1948 its specific purpose and charge was, and still is, as trustee of the District's Solano Project surface water allocation. The control and distribution of that surface water is controlled by the reasonable and beneficial standards under the California Water Code. With respect to those Codes and to the water allocations of the District, the District is committed to managing this allocation to the mutual benefit of all lands within the District's service boundaries first and foremost. The need to equitably distribute the water resources of the District to its constituents therefore necessitated the development and implementation of a water allocation policy.

The Policy is intended to be used as a guide for the District and its Board to equitably distribute its' surface water resources within the service area. The Policy established several guiding principles in addition to an allocation procedure.

Guiding Principles. The guiding principles presented below are intended to illustrate the basic assumptions that were used to develop the policy. The guiding principles are as follows:

1. The District's obligation under California Water Code is to manage and deliver surface water resources under its charge in a reasonable and beneficial manner.

2. All agricultural lands within the District boundaries have an equal right to the availability of surface water, irrespective of use or crop(s) grown.

3. Annual allocation of surface water supplies will be based on a per irrigated acreage basis.

4. The determination of the allocation per irrigated acre will be made annually by the Board of Directors at the March Regular Board meeting. To the extent feasible, preliminary estimates of allocation will be published by the District in November for the following irrigation season.

5. Growers must submit crop declaration forms by February 15, to ensure that cropped acreage is included and receives an allocation. Growers can elect to use any portion of their total allocation on parcels under their control, with some exceptions as noted below.

6. The annual allocation is not transferable into future years.

7. Management and use of Solano Project carryover water, when available, is vitally important to ensure that Agricultural Water Users all benefit equally from the resource.

Allocation Procedure. The agricultural water allocation is determined by the Board on an annual basis. The decision on allocation amounts will be made by first determining the amount of surface and groundwater supplies available to the District with the Board subsequently determining the amount of irrigation water to be used during the irrigation season. Each year a Water Budget will be determined consisting of water resources available to the District as follows:

a. Solano Project (SP) annual Agricultural Allocation of 121,000 acre-feet or, the quantity made available to the District by the Solano County Water Agency. This budget is generally known in the fall of any given water year.

b. Solano Project Carryover (CO), which varies each year and could be re-set to zero if/when the Lake Berryessa Reservoir spills. The exact amount of carryover water is not known until March 1 of any given year.

c. Groundwater (GW). The District has a groundwater well network and can deliver up to approximately 14,000 AF. The District will manage its GW supply conjunctively with its surface water supply. GW budgeting depends on a number of factors (i.e. availability, impact on others, potential judicial issues, best management practices, pumping limitations as determined by a Groundwater Sustainability Agency, etc.).

After which, the Water Budget to be allocated will be divided by the total irrigable acres, as determined by crop declaration forms returned to the District, to set the annual allocation.

The District will plan to use all of its Water Budget during any given year with no limitation. A Base Allocation is established to provide growers a proportionate share based on total irrigated acres of the SP plus GW water budget. The District will also determine the amount of CO to use for the year. The CO supply will be proportioned equitably to all irrigated parcels at the beginning of the irrigation season and be added to the Base Allocation as Additional Allocation.

For some, the Base Allocation plus the Additional Allocation will be sufficient. For those that may need more water, the District will monitor the water usage within the District and may recommend an adjustment to the Board to allow for additional allocation at the July Board meeting. Doing so will allow customers the opportunity to have more allocation so long as the District's Total Water Budget for the year is not exceeded.

Once the annual allocation per irrigated acre has been determined, the District will assign a total allocation to each customer based on the acreage under the customer's control as determined on the crop declaration form. The customer may use any portion of their total allocation on individual parcels under their control within the District during the irrigation season, with one exception. For newly irrigated parcels (parcels which have not been irrigated within the prior three seasons), all water assigned to the newly irrigated parcel may not be transferred to other properties whether under control of the customer or not. Water assigned to newly irrigated parcels must remain on said parcel and be used for three consecutive irrigation seasons prior to being eligible to transfer other properties under the customers control.

CHANGES TO THE CAPITAL IMPROVEMENT PLAN

The realizations developed by the Study and the direction provided by the District's Plan created a situation in which the District's Capital Improvement Plan (CIP) was at a crossroads. District staff realized that the former CIP, mainly including pipeline replacement projects, was not only unachievable with current funding levels, but the continued implementation wound not adequately address the chief District needs. Rather than moving forward status quo, waiting for the inevitable shortages to occur, the District took the initiative to re-develop the CIP to include projects that will better serve the future needs of the District. While rehabilitation and replacement projects are still necessary, only a portion of CIP funding was dedicated to facility projects. A majority of CIP funding is now reserved for projects that develop new water sources, improve the efficiency of the distribution system, and recover water that was historically lost in the drainage system.

New Water Sources

The most obvious method for decreasing surface water supply shortages is to obtain new water sources. The State of California operates the North Bay Aqueduct (NBA), which traverses Solano County. The District does not currently use any NBA supply but is investigating the opportunities to add the NBA to the District's water supply portfolio. The District was also identified as a net groundwater recharger in the Study. Increased groundwater production can also provide supplemental supply during surface water supply shortage years.

Water Transfers. Several of the cities within the District have a contract with the State of California to receive an allocation of water from the NBA. The NBA receives water from the Baker Slough in the Sacramento-San Joaquin River Delta (Delta) and terminates just outside of the City of Vallejo. The water delivered by the NBA has varying levels of quality, which make it undesirable for potable water treatment. The District is looking into the possibility of water transfers for greater than 1:1 ratio of NBA water, which is of acceptable quality for agricultural purposes, for higher quality Solano Project Water.

Groundwater Pumping. The District operates and maintains 23 groundwater production wells. In addition to the groundwater production wells, the District has old wells with casing or equipment that has exceeded the useful life. The District will be implementing projects to replace or rehabilitate the idle wells, thereby increasing the District's ability to produce groundwater. The goal of the well rehabilitation projects is to utilize a portion of the District's net groundwater recharge volume without overdrafting groundwater supplies.

Groundwater Recharge. Currently, the District does not utilize an intentional groundwater recharge program. As noted in the water balance section, some groundwater recharge is provided through seepage and deep percolation of imported Solano Project water. If groundwater use within the District increases in the future beyond the current safe yield, additional artificial recharge will need to be considered.

Increase System Efficiency

Several factors were identified in the Study that attribute to the efficiency of the distribution system. Distribution system efficiency is increased through the decrease of system losses. The three categories of losses from the distribution system are evaporation, seepage, and spillage. Since the volume of water lost to evaporation is small, the cost to benefit ratio does not existing for undergrounding the canal system. The District has found that spill reduction, and to some extent seepage reduction, have much higher cost to benefit ratios.

Reduce Spills. The District has been investing money in SCADA annually since 2008. To date, the District has installed SCADA sites on 15 spill sites so that Watertenders may have real-time data for spill levels and flows throughout the system. The spill sites also collect and store historical data for future reference. The introduction of the existing SCADA spill sites has decreased spill volumes by approximately 3,000 AF per year. The District plans to continue providing an annual budget for the installation of SCADA on spill sites with four spill sites projected to be installed during the 2016 irrigation season.

Automation. The largest portion of the CIP funding has been committed to the automation of the District's open canal systems. Prior to the 2017 irrigation season the District is installing Rubicon Water's Total Channel Control (TCC) solution on the largest lateral off the PSC, the Vaughn Canal. The automation of the Vaughn Canal has a two pronged benefit: the automation will provide growers the water delivery flexibility of an on-demand system while continuing to use the District's existing open canal and the project will eliminate all spills from the Vaughn Canal system, estimated to save approximately 240 AF annually. In addition to the Vaughn Canal system automation, the District has budgeted for the Weyand Canal system automation in 2017 and 2018. The Weyand Canal system is the next largest diversion from the PSC and the automation will provide the same benefits as the Vaughn Canal system automation, resulting in an average annual water savings of 540 AF.

In addition to the automation of the open canal systems using the TCC solution, the District has been working with Schneider Electric to receive a proposal to automate the Weyand Pipeline system, a network of pipelines open to the atmosphere. The project is not currently within the District's CIP, but will be added to the CIP once a budgetary figure is generated. The project will automate all the grade-wall gates and turnout gates within the Weyand Pipeline system to provide autonomous system regulation. The automation will provide increased system flexibility to meet grower's delivery requirements and reduce spills, in conjunction with the Weyand Canal system automation project, by over 1,300 AF per year.

A second type of automation project included in the new CIP is the installation of variable frequency drives (VFD). Since 2010, the District has been improving pumping plants with multiple, fixed speed, pumps. Typical practice is the installation of a VFD on the largest pump, enabling the pump to produce the same flow rate as the smaller pump(s) but with greater efficiency. The small fixed speed pump(s) are no longer used except during periods of peak demand, when the required flow rate into the system is larger than the full speed capacity of the VFD pump. In addition to the VFD, the District installs SCADA at the site to enable remote monitoring of the facility, remote control of the facility, and automation of the facility to operate on either flow control or pressure control. The District will install a VFD and SCADA at one pumping plant facility for the 2016 irrigation season, with future projects to complete automation of the remaining four pumping plants by 2024. With previous projects, the District has already automated five pumping plant facilities.

The newest automation project type the District started investing in is the automation of groundwater wells through the installation of VFDs and SCADA. Most of the District's groundwater wells are used to supplement system capacity during times of peak irrigation flow demand. Historically, the District was required to reduce surface water diversions when day to day flow changes are less than four CFS and the distribution system is running at or near capacity. Since the groundwater wells are fixed speed, the wells produce a fixed flow rate. Should a decrease in system flows be required and that reduction is less than the production of the groundwater well, the groundwater well must remain on while surface water diversion is reduced. The installation of a VFD will allow the production rate of the groundwater well to be reduced proportionately, saving the District on energy costs and the unnecessary pumping of groundwater. The first groundwater well was automated in 2012 during the installation of a new well. The CIP has budgeted funding in 2016 to add VFDs and SCADA to five (5) additional groundwater wells. In addition to the five groundwater wells that are part of the Deepwell VFD and Automation Project, the District is going to add SCADA to two spill sites that are not included in the recurring spill SCADA funding. The two spill sites are within the same system that four of the groundwater wells pump in to. The SCADA system will monitor groundwater production, spill levels, and spill flows to adjust the groundwater production to minimize spills. The goal of the project is to eliminate spills from Weyand Pipeline system, saving the District approximately 800 AF of water.

Water Recovery

After District staff considered the options of new water sources and reduction losses, staff determined the final water generating method is the recovery of District and grower losses. The projects within the recovery classification either recover distribution system spill before the volume goes over the spill or captures the water just before the water leaves the District.

Outflow Recovery Structures. The District maintains an extensive network of drainage facilities designed to convey tailwater from the irrigated lands and spill water from the distribution system into the County's drainage channels. The drainage channels then convey all excess water past the District's boundary, through the MPWD, and into the Delta. Currently, the District has no method of capturing the water for re-use and measurement of the volume of water leaving to the MPWD are of limited accuracy. The drainage channels that convey water out of the District are listed in Table 4 along with the associated, estimated volume of water available for recovery.

Table 4. Spill Volumes by Drainage Channel.

Facility	% of Operational Spills	Volume (AF)
Sweeney Channel	38%	12,300
Ulatis Channel	16%	5,200
Sawtelle Drain	13%	4,200
Brown/Alamo Channel	10%	3,200
Gibson Canyon Channel	2%	650
Other	21%	6,800

During the 2016 irrigation season, the District's CIP funded, in conjunction with a USBR grant, a recovery structure project in the Sweeney and McCune Channels. The Sweeney-McCune Creek Outflow Recovery and Automation Project includes the installation of two long crested weirs for the impoundment of spill and run-off waters, two turnout structures for lift pumps, and two automated gates for the regulated release of water to the MPWD. The recovered flows will be diverted to the adjacent landowner for irrigation of 400 acres and to the District's Weyand Canal Lateral 4 system. The use of recovered water by the adjacent landowner will relieve 10 CFS of capacity in the District's Kilkenny Canal system and up to 20 CFS of capacity from the District's Weyand Canal system.

Projects to construct recovery structures in three of the remaining channels have been included in the District's CIP plan as place holders without funding or construction dates. Once the District has constructed the Sweeney and McCune Channels recovery structure and proofed the concept, the remaining recovery projects will be budgeted in the CIP.

Regulating Reservoirs. Certain parts of the District's distribution system are not good fits for a TCC solution due to the system's size, configuration, or cost to benefit ratio. To reduce spills in systems that do not work with TCC, the District will install regulating reservoirs. The regulating reservoirs provide a storage location for any excess water in the system that would typically spill out of the end of the system. The regulating reservoir is a buffer, similar to a hydropnuematic tank on a pressurized system, allowing excess flow in the system to be stored until such time the flow can be introduced back into the system to supplement capacity. The regulating reservoirs are conceptual projects in the CIP with no plans of implementation until after 2025.

Changes in other District Programs

Prior to the Study, the District practiced an 'open door' policy for landowners wishing to annex to the District. Once the District reviewed the results of the Study and the forecasted shortage of surface water supply, the District was required to change the annexation program. As of January 2015, all annexations, in progress or pending future, were placed on hold. The District has not accepted any annexation applications since January 2015 and will maintain a moratorium on all annexations until such time the District has excess water available.

LESSONS LEARNED

During the five-year process that transformed the District's CIP, the District learned several lessons. With the ability to look back on the projects and process undertaken by the District, staff has the insight to recognize where improvements can be made. The District hopes that this section will assist other agencies navigate the path of updating their CIP to meet unknown future water demands. The District has determined that communication is the key concept for any process, there is a sequential order for each of the processes the District undertook, and that information cannot be ignored.

Communication

As with any project, communication between the involved parties is the key to being efficient and successful. During the beginning of the processes, in 2011, staff lacked communication with each other. The District's former General Manager decided to apply for a USBR grant to fund 50 percent of a System Optimization Review (SOR), which was subsequently awarded. The idea seemed sensible, as the scope of the SOR included completion of a water balance and Strategic Plan, both of which were already underway, but the District lacked the resources to complete all three simultaneously. In addition, the simultaneous projects required staff from different levels and departments, which led to intra-District communication breakdowns, where information typically only flowed from point to point. Instead of information bypassing other staff with roles in the project(s), the information should be distributed uniformly. It's understandable that many people get frustrated with being cc'd on emails not pertinent to them, but the accumulated emails provide context and reference for all parties. Lastly, clearly defining each staff's role in the project(s) is an important task. Clear definition of duties can prevent breakdown in communication between the required staff and establish a scope of work each staff is expected to perform.

Order of Processes

As described in the Communication section, the SOR commenced nearly simultaneously with the Study, Plan, and evolution of the CIP. The implications experienced with the concurrent projects were: the Plan relied on information from the Study, the SOR required information from the Study and the Plan, and the evolving CIP needed results from the SOR.

Water Balance Study. The Study is arguably the most important piece of information required to transform the District's CIP. Since every other project the District endeavored relied on the Study, the Study should be the first objective for any agency. The Study develops critical information required to determine the content of a Plan, is an item necessary for the completion of an SOR, and is influential in modifying the CIP to achieve the District's future needs.

Strategic Plan. The next step, if not already completed, is the development of a Plan. Many agencies already have a Plan without ever having performed a Water Balance Study. This is a perfectly acceptable, as a Plan provides the agency with a very distant outlook for the direction of the agency. If an agency has not developed a Plan, the completion of a Water Balance Study will be advantageous to the development. For agencies with Plans in place, the Plan will likely need to be modified based on the results of the Water Balance Study. Plans provide a 10-plus-year outlook to guide the direction of an agency. Study results, as in the case of the District, can paint a very different picture for the near future. In order for the vision of a Plan to be achieved, the agency must account for the implications encountered along their path.

System Optimization Review. The SOR is not a necessity for agencies wanting to develop or improve a CIP that is designed to meet future water requirements. The SOR would be very helpful to agencies that do not have a CIP in place and need to establish a set of projects as a jumping off point. In addition to the benefit of providing a starting point for a new CIP, the USBR provides grant funding to assist with the cost of the SOR, and the SOR increases and agency's ability to secure future grant funding for projects identified within the SOR.

Capital Improvement Program. The District was fortunate with the premature evolution of the CIP. District staff happened to be up to date and insightful enough to begin implementing projects that addressed the water shortage identified by the Study prior to the Study being completed. Ideally, the modification or creation of the CIP would occur after the SOR has been completed. When evolving the CIP, the agency needs to make sure the CIP makes the appropriate improvements to address the findings of the Study and aligns with the vision of the agency as identified in the Plan. The SOR will identify projects that take into account both the Study and the Plan, but the SOR is not necessary if the agency has the resources to develop the CIP.

Addressing the Challenge

When any great leadership is faced with adversity, the challenges must be received and addressed. The District was not prepared to receive the results of the Study, forecasting a reality that the District's existing surface water supplies would not meet future irrigation demands. Particularly difficult to accept was the unknown of which of the six scenarios, or seventh, or eighth scenario that will represent the District's actual future. The most important action District management took was to ignore the favorable Scenarios 1 and 2 and plan for the worst case, scenario 4 (2024) (Scenario). The reason the selection of the Scenario is so admirable is because the Scenario is the most difficult to address. During the development of the District's Plan, District management ensured that the Plan addresses the challenges of the Scenario. The Scenario is accounted for in the Plan's Mission, Vision, and Values. The Plan also identifies the type of projects recommended by the SOR and Study to assist in meeting the requirements of the Scenario. Next, the District's management put the Plan and SOR results into action by evolving the CIP to develop projects that will help the District meet future water needs. Finally, the CIP projects are being implemented, with plans to continue implementing the new type of projects. The evolution of the CIP was a difficult task for District staff to get everyone on board with as the new CIP has very few projects reflective of the old CIP, the types of projects the District has performed for the previous 50 years.

CONCLUSION

The transformation of the District's outlook and Capital Improvement Program has been rapid and absolute. Within the last five years, the District learned about a future water shortage from the Water Balance Study, developed a Strategic Plan to guide the District through the challenges of the future water shortage, adopted a Water Allocation Policy, completed a System Optimization Review to develop feasible projects to address the future water shortages, and evolved the Capital Improvement Program to implement the projects necessary to prevent the future water shortage. The transition was full of obstacles and uncertainties which were overcome through tenacity, insight, and teamwork. Hopefully the process performed and lesson learned by the District will be valuable to other agencies as those agencies navigate the path of evolving their Capital Improvement Programs.

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SURFACE AND GROUND WATER MANAGEMENT IN PAKISTAN

Sajid Ali Bhutto[1]

ABSTRACT

Pakistan, like many other countries, has over time moved to the limit of water stressed state and is on the verge of entering water scarcity range mainly due to population explosion and climate change. Pakistan has an agriculture based economy. Due to low rainfall, the agriculture depends on availability of irrigation supplies. The low level farmer education and training is retarding the adoption of latest water management techniques.

The surface water shortfall resulted in heavy dependence on groundwater to supplement the surface water to meet the agricultural demands. With time the groundwater harvesting (exploitation) has reached dangerous levels. The groundwater table is falling at a rapid pace and approaching catastrophic levels.

The conjunctive use of surface and groundwater in traditional ways which till recently appeared to be a fully viable option is losing ground due to static quantum of surface water and rapidly depleting subsurface aquifers of fresh water fit for agriculture.

In additional to agricultural demand, the requirement of nonagricultural uses like industrial, domestic, sanitation and environmental is also rising rapidly. The gap between assured availability and demand is increasing. Pakistan is now caught up by the dilemma about the corrective steps to induce sustainability in the supply demand management. Following options are being considered and implementation started:

(a) Adopting hi-tech irrigation systems to economize unit agricultural use.
(b) Create storages to retain the surplus flood waters that are brought by the rivers or other streams during summer monsoon.
(c) Induce discipline in groundwater harvesting.
(d) Take steps to recharge the groundwater aquifers at least locally in critical patches if not over large areas.

This paper presents the above scenario in detail with necessary data and recommendations for further actions to identify and implement sustainable remedial measures.

INTRODUCTION

Pakistan has an agriculture based economy, employing 40% of work force and contributes about 21% to the DGP and 60% of the export budget.

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The country was very comfortable regarding water availability in all provinces at the time of gaining independence. The annual surface water availability per capita was over 5000 cubic meters. Due to population increase, the country over the years like many other countries of the world, moved to the status of a water stressed state and the present annual surface water availability per capita has come to a bare 1100 cubic meters, sounding a water crisis alarm.

The available surface water is substantially short of the requirement even for meeting the crop requirements. This shortage of surface water has triggered the phenomenon of conjunctive use and heavy dependence on ground water for supplementing the agricultural demands.

GROUND WATER SUPPLEMENT

Excessively heavy utilization of ground water has caused the dependence on ground water supplement to meet the requirement of agriculture, industrial municipal and domestic use and other minor demands. A recent assessment of ground water use has indicated that about 60 MAF of the ground water are being harvested annually mainly for agricultural use, affecting the ground water with serious reduction in depth to water table.

More than 70% of the population depends on ground water for drinking and other municipal requirements. Unfortunately the ground water in the country is still considered as freely available resource without a proper management system or discipline in force. This has resulted in installation of over one million private tubewells of varying capacities:

The investment on these private tube wells is of the order of Rs. 60-80 billion whereas the annual benefits in the form of agricultural production are estimated at Rs. 400 billion, roughly equivalent to 5% of GDP. In addition, many industries rely for their water supply on relatively 'clean' groundwater.

In the case of drinking water the major concern is groundwater quality. There are several problem spots, mainly in urban areas and around rural industries, where groundwater quality is contaminated with sewerage effluents, oil residues, chromium or other contaminants. This holds true for major cities, where a large number of households still depend on individual wells for water supply. The absolute shortage of drinking water in some urban areas is posing questions for the future. The prime example is Quetta

The intensive use of groundwater has changed the water management scenario. Rapid development of shallow tubewells in the Indus Plain resulted in the spectacular increase in productivity and made up for many of the deficiencies in water supplies in the world's largest contiguous surface irrigation system. This is illustrated by the stabilization of grain production during the drought years 2000-2002, with shortfalls to a large part made up by the use of groundwater. The intensive use of groundwater, however also requires more intense management - to address problems of a declining water table, saline water ingression/and groundwater quality

CURRENT USE IN DIFFERENT PROVINCE

All the four provinces in the country are mining the ground water uncontrolled and in many areas the excessive pumpage has resulted in serious overall lowering of ground water levels to the extent of becoming precarious in some locations.

The extent of pumpage by the four provinces is depicted in Table 1 which exhibits pumpage of 47.4 MAF by Punjab, 7.8 MAF by Sindh, 1.2 MAF by KPK and 3.63 MAF by Balochistan making a country total of 60.0 MAF.

Table 1. Province-Wide Tubewell Number and Type of Prime Mover: Annual Pumpage.

Total Number of Tubewlls/ Lift Pumps	**Punjab**		**Sindh**		**KPK**		**Balochistan**		**Pakistan**	
	Electric	Diesel	Electric	Diesel	Electric	Diesel	Electric	Diesel	Electric	Diesel
	72,480	**752,399**	**31,680**	**62,850**	**9,829**	**11,020**	**14,363**	**11,371**	**128,352**	**837,640**
Days per Year	183	124 151		123	152	108	227	189		
Hours per Day	6	5 7		6	4	5	7	5		
Discharge (cfs)	1.5	1 1.5		1	1.5	1	1.5	1		
Pumpage (AF)	9,649,444	37,707,730	4,060,148	3,749,317	724,594	481,023	2,767,265	868,602		
Total Pumpage (AF)	**47,357,137**		**7,809,465**		**1,205,617**		**3,635,868**		**60,008,123**	

Source: Agriculture Statistics of Pakistan - 2013

URBAN AREAS

Most of major cities in the country rely on piped supply from related, water and sanitation agencies (WASAs) and private pumping for domestic water supply. The large scale exploitation of the aquifer beneath the cities and in suburban residencies has however led to falling water tables and contamination of water supplies by leaking sewerage systems.

Lahore WASA and private ground water users have been forced to increase the tubewell bore depths from 150 to 230 meters.

Hudiara drain, Ravi River and sewerage disposal via soakage pits and open ponds in surrounding villages are major source of pollution for the Lahore aquifer. Also of concern rs the municipal waste disposal - mostly without treatment - which is likely to be a major threat to the underlying fresh groundwater and downstream surface water users. Just like Karachi, Hyderabad and Islamabad, surface water allocation about 0.5 MAF would also be required for Lahore city water supply and additional recharge to the aquifer

In Peshawar, Uptil 1992, the depth of the tubewells was in the range of 40 to 57 meters in Peshawar City. By 2010 it rose to the range from a minimum 67 to maximum 183 meters (NESPAK, 2010). NESPAK had reported an average water table decline rate of 0.57 meter per year. NOC, 2013 had studied water table in Peshawar city and reached similar figures. So far the urban groundwater quality and quantity problems go unaddressed.

In Quetta the over-exploitation of the confined aquifer by agricultural users around the city has already led to a number of gloomy projections, under that in foreseeable future even the deep groundwater under the capital of Balochistan province may dry up.

In the Malir River near Karachi the disturbance of the riverbed to excavate for stone products has resulted in a limited recharge of water flows and reduced water levels in wells in the adjacent area. Similarly the catchment of Lai Basin, feeding the twin cities of Islamabad and Rawalpindi is disturbed by quarrying and deforestation. In addition, the rapid growth of the built-up area, the increased and unregulated private domestic consumption and the disposal of untreated or semi-treated sewerage in Islamabad and Rawalpindi has led to a decline in the water table at 1.4 meter annually and an estimated 90% of the drinking water wells being contaminated with coliform bacteria (Malik 1998).

Firm and dedicated efforts are needed to detoxify the urban and suburban waters to the benefit of the users by providing protection again contaminants.

CHALLENGES

The management and use of groundwater is faced with a number of challenges.

Some common attributes are:

- Progressive depletion of groundwater particularly near urban centers & in canal commands with lower water allowance.
- Strong evidence of deterioration of groundwater quality including pollution.
- Increased pumping costs.
- Salt accumulation in root zone due to more dependence on groundwater.
- Due to deterioration of groundwater in Peshawar Basin, surface water supply is planned to meet demand of Peshawar City.
- Water logging increasing in Sindh

In Balochistan Province

- Irreversible groundwater depletion in Quetta-Pishin valley due to indiscriminate exploitation.
- Deep well pumping has dried most of the Karezes.
- Cost of pumping is more than three times the revenue due to deep pumping.
- Subsidized tubewell tariff for agricultural tubewells resulted in excessive mining.
- Steep land slopes do not let water to percolate .
- Massive removal of vegetative cover having negative impact on precipitation.

The common denominator in all these challenges is that a start has to be made in addressing resources dedicated to the water sector reverse lowering of water table. Though the intensive use of groundwater has boosted the economy for years, the lowering of the water table in barani areas has at the same time caused considerable hardship. It has undermined livelihoods and affected the availability of drinking water and generally increased vulnerability to droughts. It has also changed access to groundwater in the barani areas. In the canal commands the overuse and lowering of the water table increases pumping costs and induces ingression of saline water into fresh groundwater areas.

The drought of 1997-2002 caused groundwater. Worst hit areas were the parts of Quetta - Pishin in Balochistan, Tharparker in Sindh and Pothohar Plateau and Cholistan Desert in the Punjab where large number of wells went dry or saline. In many areas groundwater exploitation exceeds sustainable yields. During the dry years this trend accelerated. According to Qureshi and Mukhtar (2004) the drought triggered outmigration of 9% of all people in the barani areas in Sindh and Balochistan.

In Balochistan 75% of the orchards were affected; animal mortality increased; animal stock reduced further because of distress. It may be argued that the presence of tube wells relieved the effects of the drought, but the issue is double-edged, because overall the falling water table reduced resilience and made it more difficult to find alternative sources of water.

The decline in water tables has also caused changes in access to groundwater. In the past the most common form of groundwater exploitation in Balochistan was the dug well. Not everyone had access to a kareze and when dug wells came in vogue, they were often financed by farmers that did not have a share in the kareze. Over time both karezes and dug wells fell dry and deep tube well became the most viable option. The cost of these deep tube wells is high (Rs one million and more) and can only be afforded by a privileged/ effluent few.

This increase in pumping cost with the decline in water tables is a general trend. In the unconfined shallow aquifer of the Indus valley for instance centrifugal pumps with sumps are most common. With gradual increase in water table depth, the farmers have to deepen their sumps or deep well turbine pumps have to be used, with cost increased which are out of the reach of small farmers.

ADDRESSING WATERLOGGING

Paradoxically some areas are still suffering from water logging, mainly in Sindh and some parts of the Punjab mainly located in the topographic depressions and/or along main canals – feeders in areas with high irrigation duties and/or saline groundwater. SMO-IWASRI, WAPDA data indicates that 5 to 15 % of the irrigated land is still waterlogged and about 5 % suffers from severe salinity. Improved irrigation efficiency and better drainage facilities are proposed to mitigate this.

GOVERNMENT OF PAKISTAN POLICIES/APPROACH FOR GW MANAGEMENT & REGULATION IN THE PAST

Government of Pakistan policies in the past were mainly oriented towards development and management of groundwater resources with main emphasis on providing drinking/irrigation supplies and meeting drainage requirements, particularly, in saline groundwater areas. The policies formulated from 1873 to 1979 were, mainly, aimed at the regulation of canal supplies, eradication of water logging and salinity rather than controlling/restricting the use of groundwater as no scarcity was ever felt. With the increasing pressure on the groundwater regime and water table from rising to falling (in general) we had to think of the sustainability of the resource which is the life line for more than 90 million people – *<u>the policy landscape changed from "development to management from 1980s."</u>* GOP's previous legislation concerning groundwater development/use, were as below:

- The Canal and Drainage Act VIII of 1873
- Punjab Soil Reclamation Act, 1952
- West Pakistan Water and Power Development Authority (WAPDA) Act, 1958 / WAPDA Act, 1975
- Punjab Local Government Act, 1979
- Pakistan Environmental Protection Act, 1997
- Reforms in the Irrigation and Drainage Sector, PIDA Act 1997 and subsequent amendment in Canal & Drainage Act Clause 62 - A, in 2006.

Which lays down:

Section 62-A was prepared to enable GOP to take steps in order to:

(a) Improve the groundwater knowledge base, and
(b) Develop and introduce groundwater management schemes taking into account the conditions prevailing in different areas of the province, with the participation of stakeholders.

The above section 62-A conform a broad framework for improvement of implementation efforts.

<u>Groundwater Modeling and Framework under LBDC Project</u>

Water resources in the LBDC command are under intense pressure and the quality and quantity of groundwater are deteriorating rapidly. Utilization of groundwater is now integral to agricultural production but the present rate of groundwater abstraction is not sustainable because the depth to water table is fast approaching the maximum depth at which the commonly used pumping technology can perform. Accordingly, consultants - Lahmeyer International GmbH, Germany and National Development Consultants (Pvt) Ltd conducted detailed studies, developed mathematical groundwater flow model and GWRF for sustainable use. The recommended framework for groundwater management is based on:

- Sustainable management of land and water resources by stakeholders and includes regulatory framework and water rights, economic instruments, awareness raising and stakeholder participation;

- Sustainable use of the aquifer wherein the groundwater quality and quantity are stabilized by resource monitoring and evaluation, contaminant and pollution control and managed recharge and abstraction.

Groundwater Regulatory Framework – under Development

Under the groundwater monitoring and management project groundwater regulatory frame work is being up dated keeping in view the existing groundwater, social, economic conditions. The framework - after completion will be processed for a legal enactment.

PRIORITY AREAS FOR ACTION

Most of the groundwater issues in Pakistan need better management. At present the groundwater sector is predominantly a private affair, requiring regulation rather than financial support. Regulation needs to be seen in a broad context – depending on the location either stimulating private groundwater exploitation or restricting it. There is a need to revisit the current institutional and financial arrangements in groundwater. Public funds in the groundwater sector in particular should not be directed at subsidizing overexploitation, but at augmenting supplies improving local groundwater governance and controlling groundwater contamination and overuse.

The priority areas for action of foremost concern:

- Re-examine irrigation duties in canal command
- Promote and support local groundwater management
- Avoid groundwater disasters at hot spots
- Initiate institutional coordination
- Stop financing overuse
- Invest in recharge
- Tackle groundwater pollution in selected places
- Rainwater harvesting;
- Adoption of high efficiency irrigation system.

Re-examine Irrigation Duties

In canal commands the most important strategy in balancing supplies and demand in groundwater is to re-examine surface water supplies. With close to 1000,000 tube wells in use, the conjunctive water use in fact presents itself as the most powerful mechanism for water management. In canal commands with fresh as well as saline groundwater alike, farmer use a mix of surface and groundwater supplies. A systematic integrated strategy at system level, however, is missing.

During this drought period the shortfall in water delivery was compensated by intense groundwater use and by more efficient irrigation. As the figures from Sindh show there was a concomitant dramatic reduction in the area under waterlogging – indicating that drainage conditions would also benefit from reconsidering irrigation duties. At present water allowances in the perennial canals range from 2.8 cusecs/ 1000 acres (LCC, LJC in the Punjab and Eastern Nara and Rohri canals in Sindh) to 7.7 cusecs per thousand acres in Kalri – Bhaggar Feeder in Sindh. For non-perennial canals the water allowance varies from 3.5 cusecs in the command of UCC (in Punjab) to 17.6 cusecs/ 1000 acres (Rice Canal, Sindh). There is no reasonable justification for these differences, particularly because they trigger wasteful water use in the top-end commands.

So far the issue of re-examining canal supplies has been a political no-go area. However, there has never been a systematic discussion on the merits, including the possible impact of releasing water for other areas and the considerable benefits of reduced water logging for health and property. A strategy for re-examining canal supplies would need to incorporate a systematic information campaign to avoid dysfunctional polarization.

Promoting and Supporting Local Groundwater Management

To regulate groundwater outside the canal commands the promotion of local groundwater management is the most promising avenue. In few valleys in Balochistan, i.e. Panjgur, Kech and Mastung, kareze shareholders in the past took spontaneous initiatives to control groundwater exploitation and prevent overdraft (van Steenbergen 1995). In other areas the response to declining water tables was to activate the traditional harim (border) rule. These spontaneous arrangements – though few and far between - are so far the only examples of groundwater regulation in Pakistan. In areas with relatively small confined groundwater systems, there is scope to promote such local regulation systematically and on a large-scale.

There is a need, however, to revive the effort. A broad-based awareness campaign on the limits to groundwater utilization and on effective actions to reverse overuse should be part of this. In the social environment that exists in Balochistan but also in other arid tribal areas in Pakistan, where it is extremely difficult to enforce any regulation which individuals or tribal groups judge, the only way to ensure that policies and laws are implementable is through consensus building and intense education and communication programmes. Participatory hydrological monitoring and local micro planning should follow up from the campaign. In participatory hydrological monitoring groundwater users are being facilitated to measure groundwater fluctuations and prepare local groundwater budgets.

Institutional Measures

Institutionally groundwater is nowhere and everywhere at present. More than a dozen agencies have been involved in groundwater development and monitoring, but lack coordination, proper staff availability and adequate logistics. None of these agencies has complete knowledge of the issues and none has operational responsibilities in groundwater management. What is required is to develop a focal point within each provincial administration that will promote and enforce regulation, coordinate the activities by various agencies and gradually develop a database. Ideally, one provincial agency would be overall responsible for groundwater monitoring, management and regulation. According to current legislation the Provincial Irrigation and Drainage Authorities have this task. The PIDAs are to ensure that groundwater monitoring is undertaken and have a mandate to initiate policies to address groundwater management problems but related actions are not viable. In other comparable countries in the region, special full-fledged units have been created in the main irrigation or water resource departments (for instance Egypt) or special departments, closely attached to water use departments have come into force (West Bengal, Andhra Pradesh, Maharashtra in India). This is very much the need of the day, particularly in Balochistan and Punjab Province, where the dependence on groundwater is heavy. It is proposed that where Provincial Irrigation and Drainage Authorities are in place and capable such Groundwater Cells are set up in the PIDA or the Planning and Development Department. The Groundwater Cells will coordinate the data collection by the most competent parties, not necessarily undertake it itself. The establishment of the Groundwater Cells needs to be supported fully.

Presently, data on aquifer characteristics, groundwater levels and groundwater quality, in as far as they exist, are scattered over various organizations. The most comprehensive data sets are those with SMO, but their coverage is limited as they were mainly collected to assess the performance of the SCARP wells in controlling water logging. Information sharing should be part of such monitoring programs, communicating results to local media, decision makers and key stakeholders.

ACTIONS REQUIRED

Irrigation System

- Re-examining water allocation for different canal commands, keeping in mind official irrigation duties, actual deliveries, cropping patterns, groundwater quality, current groundwater use and over- or under-exploitation.

- This needs to be complemented by an extensive information campaign free of politicization.

- Promote skimming wells in areas with saline groundwater to exploit the fresh water lens on top of the saline layers.

- Conjunctive use may be remodeled to increase the fraction of above margin salinity.

Institutional Measures

- Initiate an awareness campaign that familiarize groundwater user on the local aquifer conditions, risk of over exploitation, legal provisions, water conservation measures and importance of local management

- Initiate a social mobilization programme to develop local groundwater regulation, focused on participatory hydrological monitoring and micro-planning. Engage tehsil administration in these efforts

- Strengthen capacity of Farmer Organizations to manage water resources through training programmes and local water budgeting

Technical Measures

There are several meaningful programs and policies that can be pursued to counter these threats. The following actions are to be taken at expert level:

Prepare/update hydro-geological maps & groundwater atlases for the benefit of decision makers and farmers. Investigate and reverse groundwater contamination. Prepare water storage project sand implement them.

Surface Water – Availability and Demand. The quantity of surface water available for use in Pakistan is almost static and fully utilized, but requirement for agricultural uses is not met and cultivators have to the varying extents switch over to exploit ground water for conjunctive use to enhance the cultivated area and the produce.

The groundwater available in underground aquifers is basically not quantified and is taken as everlasting, which is a fallacy. The ground water is being used through tubewells numbering over 1.1 million in the country out of which the private sector tubewells are quantified at about 1 million and public sector owned are only about ten thousand. The pumpage being uncontrolled is generally resulting in substantial lowering of groundwater levels.

Conjunctive Use. The conjunctive use of ground water with surface water, developed to more than the actual requirement causing serious lowering of groundwater table and increasing pumpage costs. The excessive mining is also supported by heavy subsidies allowed for installation and operating of tubewells including low electricity charges.

Adopting High Technology System. The high technology / high efficiency systems have been recently introduced and are gaining popularity but high cost and low educational level of users are the retarding agents. These two handicaps along with encouragement to local manufacture of hardware need immediate redressal steps.

Inculcating Discipline in Groundwater Harvesting. Groundwater harvesting / mining has been an activity with no discipline, technical, agricultural and financial. Inducing discipline into this activity will at-least stop the decline in groundwater levels and the storage used in tandem can bring up the groundwater table levels to comfortable normally.

Recharging the Aquifers. The dwindling aquifers need immediate support through recharge. The various recharging methods are being considered and a pilot project involving the use of an inflatable rubber dam is being taken up to recharge the critically discharged aquifer of Bahawalpur city. The rubber dam is proposed to be installed in Sutlej River located close to the city. This activity need to be pursues vigorously.

Rain Water Harvesting. The application of the rain water harvesting concept has widespread field of uses, but it can only be exercised usefully in high rainfall areas. In Pakistan the water scares desert areas like Cholistan and Thar are the only tracts where rain water, though meager in quantity is at-least partially harvested and stored in makeshift or natural ponds enclosed by sand dunes, to be used for general consumption by the desert residents. Up north where rainfall is normally in medium range i.e. 1000 to 1200 mm, the need for harvesting rain water is hardly recognized except for domestic use other than drinking.

Since the rainfall generates the run off that provides discharge to natural stream s, the harvesting phenomenon has to be introduced an d practiced in a pla nned and disciplined manner. Relevant organizations are however trying to propagate the concept for judicious use.

Creation of Storages. The creation of more storages to retain flood surpluses and effectively inducing the recharge of ground water aquifers has now become imperative and is rather overdue and has to be effectively managed on highest priority. The process is already recognized in principle and is being implemented though at a slow pace in all the provinces. The provinces have already constructed some small dams for this or similar objectives e.g. about 150 small dams in Balochistan, about 50 in Punjab, about 20 in Sindh and about similar number in KPK. The real need is that of assigning due priority to this urgent need.

Policy Measures

The following actions are required at policy level:

- Planning Commission of Pakistan to prioritize groundwater recharge projects. In case of groundwater recharge a broad range of recharge options – from water harvesting to spate irrigation – should be developed and used. At present funds for recharge are spent on delay action dams only, but evaluations have shown that a large number of these do not contribute to artificial recharge.
- Stop financing overuse, as now occurs through reduced electricity tariffs for agricultural use, flat rates, non-collection of charges as well as the continued and non- essential operation of public sector wells in fresh groundwater zones.

- Provincial Governments to setup Groundwater Boards with clear tasks and capacities in monitoring, data dissemination, rule setting and enforcement. Also rationalize canal water allowances, design & approve groundwater recharge schemes/projects.
- Provincial Agriculture Departments to educate farmers about aquifer characteristics and water quality issues.
- Environmental Protection Agencies to enforce regulation against disposal of untreated toxic effluents into surface drains which are polluting groundwater and surface water.
- WASAs to encourage & enforce rainwater harvesting and prepare and implement groundwater recharge scheme.

ON-FARM FLOOD IRRIGATION AUTOMATION: CASE STUDY OF INSTALLED SYSTEM IN HOLTVILLE, CALIFORNIA

Jack Goldwasser[1]

ABSTRACT

Alfalfa and feed grass production in much of the U.S. is irrigated by flood irrigation. This process is managed manually by seasoned field staff who are becoming increasing expensive and scarce. The job requires an "irrigator" to be on continuous duty for several days manually opening and closing many small delivery gates along an on-farm canal while monitoring the progress of flood waters along a field with the goal of adequately irrigating and minimizing tailwater runoff. Watch Technologies has developed and installed a prototype automated system, AutoFlood™, on a farm in Holtville, California, that fully automates the irrigation process starting when water first enters the on-farm canal from the Imperial Irrigation District through a sequence of 24 gate openings and closing until the field is properly irrigated. The system includes a central controller assembly, water-present sensors that detect water downfield of the delivery gates, and gate actuators that open and close each gate in sequence as required. The system as installed is a combination hardwire link from the delivery gates to the controller and radio link from sensors to the controller. Initial field tests were completed in February and March of 2016. .Field testing proved the viability of the hard- and software, the potential for minimizing runoff, and the economic benefits of automation.

INTRODUCTION

Flood irrigation, or surface irrigation, is as old a technique for watering fields as irrigation itself. The technology is and has been basic; install a canal to deliver water near a field at an appropriate head level to allow controlled flow through manually operated delivery gates or flash boards. The on-farm process has changed little to the present day notwithstanding massive distribution infrastructure advances installed to bring irrigation water to a farm. This paper will detail how automation technology was deployed on a farm in Holtville, California, located just south of El Centro in the Imperial Valley and consider its economic impacts.

CURRENT FLOOD IRRIGATION PROCESSES

Water conservation and labor efficiency were not the driving forces behind the historical use of flood irrigation. Today, farm labor is no longer low-cost in the United States and water has become an increasingly valuable commodity that is treated as such in the marketplace. In the desert West, grass and alfalfa feed crops account for millions of acres of farm production much of which is flood irrigated. Automation technology aimed at reducing on-farm labor costs and reducing non-productive tailwater runoff has not been available.

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Figure 1. Typical Delivery Gate

A typical field that is flood irrigated will have a modest canal installed along one side of a fairly level field with on-farm delivery gates located at regular intervals, typically 55-80 feet apart in the Imperial Valley, that bring water to "Lands" or long narrow segments of a field separated by mounds meant to facilitate sequencing flooding across the field (see Layout 1 below). On-farm delivery gates are made of light-gauge galvanized steel, more recently stainless steel, and vary in size from 12" to 18". They are embedded in the concrete lining of on-farm canals controlling flow through a short pipe running perpendicular to the canal through the levy separating the canal from a field. Once the on-farm canal is full delivery gates are manually opened by pulling its blade handle up uncovering the pipe opening and allowing flooding flows to enter a Land. Irrigators, seasoned field staff that understand the specifics of each field and their crops, are on 24-hour duty during the multi-day irrigation sequence required to irrigate all the Lands in a field. They open two or more delivery gates for each Land while keeping a close eye on the "tail" of the Land to make sure sufficient flow has covered the crop and secondarily minimizing tail-water discharge into a drainage ditch running perpendicular the Lands. The labor cost for this process ranges from $63 to $100 per acre per year. Irrigation efficiency is gauged by how satisfactorily the Land was watered and how much water ends up in the drainage ditch. Irrigation efficiency is a constant farmer concern since it directly contributes to farming profitability; flows that do not sufficiently cover the tail of the Land reduce crop yield and water in the ditch is an unrecoverable expense/resource.

AUTOMATING FLOOD IRRIGATION

In the spring of 2015, Watch Technologies was asked by a farmer in the Imperial Valley to consider automating surface irrigation. A visit to the Imperial Valley to evaluate the opportunity included interviewing a small set of influential farmers and attending an on-site presentation of current technology sponsored by the UC Cooperative Extension-Imperial County UC Desert Research and Extension Center Holtville, CA**.**

Three issues emerged that drove farmer's interest in automating flood irrigation; 1) the pool of irrigators required for the process is aging, 2) the irrigator pool was dwindling due to a lack of interest in the work, and 3) irrigators were getting more expensive. Long-term prospects for managing flood irrigation practices in a traditional manner were perceived to be fairly grim. Automating flood irrigation was an option but the only system under development in the Valley and showcased at the Holtville presentation required extensive remodeling of on-farm canal systems, installing costly new gates with control technology, and required exacting field leveling; too costly for wide-spread application with reported costs in excess of $1k/acre. It became apparent to Watch Technologies that the key to cost-effectively automating flood irrigation was a retrofit to existing on-farm delivery gates, developing an effective means to "sense" when flooding of Lands was sufficient for gates to be automatically closed, and a means to detect water when it enters the on-farm canal so the system could be activated without human intervention.

AutoFlood™

Watch Technologies' AutoFlood™ system (Patent Pending) is composed of three sub-assemblies: a blade and actuator assembly suitable for new or retro-fit applications, a radio-based Water-Present sensor, and a Controller assembly.

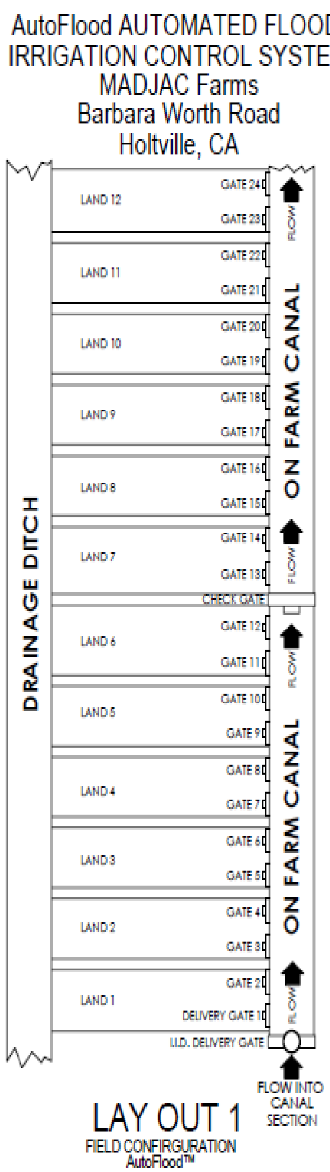
Automated Gate. The blade and actuator assembly includes a stainless steel platform that supports a linear actuator, an attached new blade with sealing lock, and solar powered electronic controls for the actuator housed in a NEMA 4 enclosure with a solar panel mounted on its lid. The entire assembly was installed by removing the existing blade and sliding the new blade in its place which at the same time located the platform on the canal wall so it could be properly attached (Figure 2)

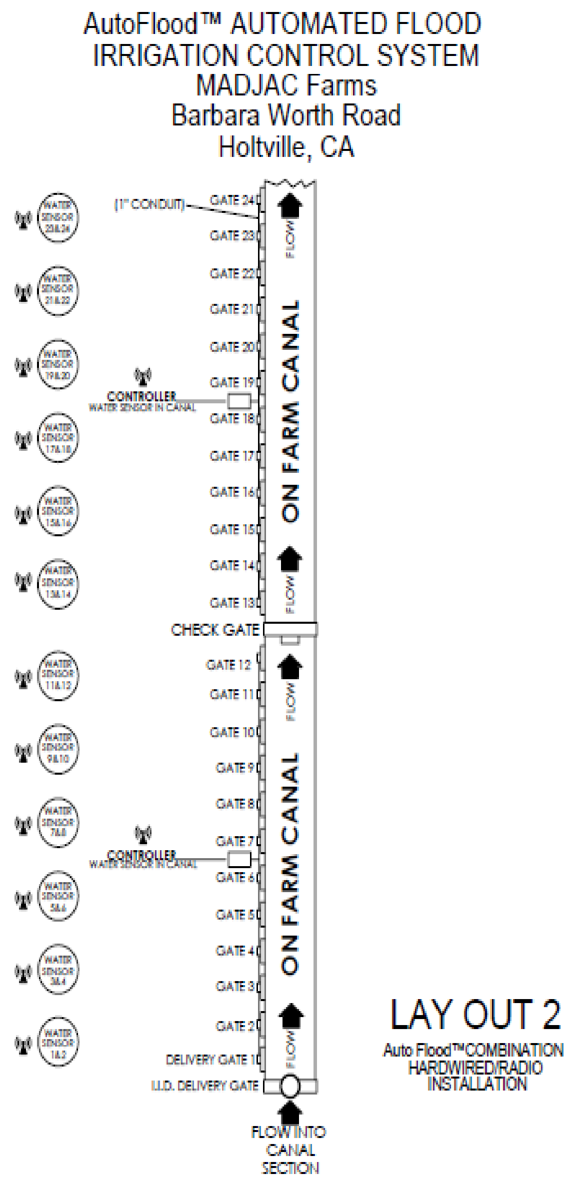
Figure 2. Automated Gate.

Water-Present Sensor. The Water Present sensor (WP) is a radio-equipped smart assembly mounted to a mast located at a convenient location down-field of a set of Delivery gates; smart because it has the capacity to manage gate assignment, incoming data, and RF transmissions. It detects surface water level and transmits that data to a Controller located along the on-farm canal which then commands delivery gates associated with that specific sensor to close.

Figure 3. Water-Present Sensor

Controller. The Controller is a radio-based assembly, typically called a Remote Terminal Unit or RTU, including a PLC-type controller that controls delivery gates based on data from the Water-Present sensor, a smart switch PCB board that when combined with a water-present sensor in the canal activate the Controller when water is delivered to the canal. The entire system is dormant until water is present for flood irrigation.





FIRST FIELD TEST FEBRUARY 18-21 2016.

Watch Technologies and Madjak Farms installed a prototype AutoFlood system on approximately 60 acres of Kleingrass on one of Madjac Farms fields in Holtville, CA. The farm is called Ash 180 after the Imperial Irrigation District (IID) delivery gate identification. The system controls twenty-four canal gates along an on-farm canal (Figure 4) linked by hardwire to two controller stations with radio links to 12 Water-Present sensors, one per Land. Each Water-Present sensor controls two Delivery gates. The first field test was conducted on February 18-21, 2016, the second March 17-19. Extensive lab-testing preceded the field application.

Figure 4. On-Farm Canal with 24 Gate Control Assemblies Installed

The Ash 180 AutoFlood system was designed to completely automate flood irrigation by first "waking up" the system when water was detected in the on-farm canal associated with the Lands to be irrigated then sequentially opening and closing pairs of delivery gates on 12 2500' x 110' Lands based on data received from Water-Present sensors initially located roughly 75% down-field of the on-farm canal. Water-Present sensors detected water at approximately 1" above the field surface.

Overall, the system worked as predicted; the system activated automatically, WP sensors reported water sending a message via RF to an appropriate controller, and gates were closed when irrigation was completed on a Land and opened on the next Land in sequence. However, there was less than 100% reliability in each of the three AutoFlood systems during the first field test.

Water-Present Sensors

The WP sensors worked as designed and lab-tested. They reported water as it covered their probes at a desired level above field surface. Initially, there was less than perfect reliability regarding transmission success to the controller; several of the installed relays once latched would not return to "off and waiting" thereby giving a false-positive water-present message. Watch's testing procedure contributed to the problem; sensors were lab and field-tested in water so it was not possible to determine if the relays were improperly latched prior to testing. Watch was able to reset those few sensors that were permanently latched in the field and thereby activate gate closures but, of course, they were required to operate without human intervention.

Controllers

Both Controllers performed as expected. The AutoFlood system for this first application used two hardwire interconnected Controllers to control 24 gates in sets of 12 gates. A few minor problems occurred marring 100% Controller performance. These problems were entirely related to software improperly reacting to out-of-sequence messages from Water-Present sensors that occurred due to the relay issue noted above.

Gate Mechanicals

The automated gates operated well responding to commands from either controller. Battery voltage remained high even though the gates were activated much more than anticipated normal during testing. No systemic electrical problems emerged. However, increasing the initial very conservative fusing limits was required to account for occasional increased electrical demand to get the linear actuators past debris accumulated in the gate guides.

Water Conservation

Watch Technologies predicted 5% net water conservation using AutoFlood over manually controlled systems. While tailwater data is available on the test farm, accurate historical data from the point of delivery was not. Imperial Irrigation District (IID) staff have their ways both traditional and technical to measure flow into an on-farm canal. In advance of the AutoFlood field test Madjac Farms requested IID install a flow monitoring device at the heading of its on-farm canal to more accurately monitor flow into the test field. Madjac historical tailwater runoff flow was reported to Watch at 8-13% of irrigation flooding flows. Following the test, inflow and tailwater discharge data were examined. Even though Water-Present sensors could have been located closer to the canal thereby reducing delivery gate-open time, tailwater discharge amounted to 4.7 % of delivery flow. Runoff reduction of 3-8% was achieved while flooding coverage was excellent.

The first AutoFlood field test clearly demonstrated that maximizing floodwater conservation using the system will require the following:

1) Care in the placement of Water-Present sensors so flow onto a Land is stopped as early as possible to limit tailwater runoff while assuring proper coverage. Mapping the site and Water-Sensor placement will eventually produce locations best suited for the time of year and crop. Permanent placement of the sensor, perhaps in the mounds separating Lands, and using selectable time-based delays in software to manage variable flow stops will be the likely long-term solutions. Implementing time stamps for all on-farm radio communications and storing them at the controller for download will provide a useful tool for managers to compare elapsed irrigation time on each Land against tailwater runoff and sensor location.

2) Careful coordination with IID so flow into the on-farm canal is stopped when irrigation on a field is complete. The obvious and best solution would be to automate the Ash 180 delivery gate such that it could close when irrigation was complete.

3) Good data collection practices are in place to calculate total flow onto each field and into the tailwater ditch.

The Ash 180 system had to keep gates 23 and 24 open even when irrigation was complete to make sure inflow to the on-farm canal had a place to go other than overtopping the on-farm canal if water delivery from IID was not terminated when irrigation was complete. It turned out that IID flow kept going for 12 hours after irrigation was complete so the precaution regarding gates 23 and 24 was important.

SECOND FIELD TEST: MARCH 17-19

Improvements in Water-Present sensor software were implemented and replacement water probes nearly eliminated the relay latching problem and allowed for better monitoring of RF broadcasting. The latching problem will be completely solved with non-latching relays installed in water sensor probes by their manufacturer. Improved transmission oversight allowed Watch to more closely monitor all component transmissions assuring accurate observations of Water-Sensor performance and controller responses. All systems improved dramatically to nearly 100% successful operations; AutoFlood worked well.

Revision 2

Field testing verified AutoFlood's performance potential. Revision 2 of the system will not change its fundamental design but changes will be made to reduce installed cost, improve reliability, and provide better data acquisition and storage for long-term operations planning.

Cost reductions will be made by converting to radio-only communication. Hardwiring the link between gates and the controllers proved costly not only for the extensive wiring but because it required special PCB boards in the controller to command gates and inherently limited the number of gates controlled by a single controller. Hardwiring was fine for prototyping but was never intended for the commercialized product. Rev 2 will have only one controller and will have no practical limit to the number of gates it can control. Reliability will be improved through component modification and manufacturing techniques. As noted above, water probes will be manufactured with non-latching relays to avoid any potential issues associated with powering the relays open after latching. Switching to surface-mount PCBs will enhance chip stability and avoid manufacturing errors. Software will be changed to time-stamp and log all operations, allow for sequencing changes and changing gate-to-WP sensor assignments, and provide the option for sending operational data to a remote Base Station.

COMMERCIAL APPLICATION

Installing on-farm automation will return economic value if it can save sufficient labor cost to warrant installation without compromising crop yield, reduce direct costs for irrigation water, and in the case of the IID, generate revenue through demonstrated water conservation. Field tests of the prototype AutoFlood system indicate the it can meet all three tests.

Labor Costs

Monitoring manual flood irrigation requires 24 hour active supervision of the process. This includes periodically measuring where water is relative to the tailwater runoff ditch on each land by "stepping-off" the distance several times, timing when water should be cut off on the Land, and then closing gates when it is assumed water flow downfield on the Land can complete the irrigation. Initial testing of the prototype AutoFlood system was never intended to replace close monitoring since the system had no performance record and placement of the Water-Present sensors down-field of the on-farm canal was not clearly understood. However, by the second test, the irrigator in charge was confident enough in the system and sensor placement to simply monitor when water "hit" the sensor probes and then watch for gate actuation at the on-farm canal. After a few more irrigation cycles, the irrigator will, at most, monitor actuation of the gates. It will be up to farm management to decide when the system has proved sufficiently reliable to allow un-monitored irrigation. Protective measures to deal with potential canal overflowing due to sensor or gate actuator failure, such as sequencing gate actuation so that at no time during an irrigation cycle will all gates be closed, gates remaining open will pass flow equal to canal inflow, and installing level sensors in the canal that trigger gate openings to assure canal level stays within an acceptable deadband, will enhance confidence..

Cost of Water and Conservation Revenue

The reason water conservation is important goes beyond the obvious need in California to use its limited resources well. Demonstrated on-farm conservation pays farmers in the IID $285 per acre foot. Given the average 6.5-7.0 acre foot allocation per acre per year in the IID, a 5% demonstrated decrease in water consumption will earn a minimum $92.65 per year per acre. Automation throughout the grass and Alfalfa flood irrigated acres within the IID (approx. 235,000 acres) could mean conserving and average of 76,375 acre feet of water with a value to farmers of $21.7 million per year.

Even though delivered water cost in the IID is low, it is a cost. Field tests have confirmed that automation will reduce tailwater runoff which will reduce IID delivery requirements. However, without active local control of the Ash 180 gate at the test site, there is limited opportunity to stop flow into the on-farm canal when desired. For example, IID needs 3 hours to get staff to the delivery gate and even if requested staff workloads and on-site timing can extend that dramatically as happened during both field tests.
At this stage in the course of on-farm flood irrigation automation two important water delivery issues need to be resolved to maximize automation value with respect to

farmers; 1) when flows onto a farm are officially "stopped" for purposes of billing and 2) accurately calculating flow onto the farm with the purpose of demonstrating conservation against historical use. Agreement on how to calculate flow into the on-farm canal is a more complicated task and beyond the scope of this paper but it has everything to do with how IID will determine the value of conserved water.

Cost vs. Benefit

The AutoFlood system as installed with hardwire connections to the controllers would cost $39,196 or $516 per acre on a field like the prototype site with 24 gates at 55' spacing assuming 2 gates per Land and 2500 ft. deep Lands; roughly 77 ac. Yearly maintenance is negligible. Projected installed cost for Rev 2 on the same field is $30,796 or $407 per acre.

Assuming proper placement of the Water-Present sensor, a farmer can expect to conserve 5-15% of flood water requirements based on current modeling, fields tests completed, and historical use. In the Imperial Valley where irrigation typically requires 6-7 ft of water per acre per year, the value of conserved water using the lowest projected conservation value, $7134, would pay for the installed system within 5.49 years, the Rev 2 radio-only commercialized system in 4.3 years

Labor savings are hard to calculate at this point without a commercialized system in place for a season or more. Given that an irrigator would be able to manage several fields at a minimum rather than one or two at a time will reduce costs dramatically. Irrigators will no longer have to measure distances or estimate flow times downfield or manually operate the gates. Assuming a farmer with several to many fields, the irrigator position will be changed from fairly labor intensive to one of monitoring and management with a likely renegotiation of responsibilities and compensation. It is reasonable to estimate reducing the cost of irrigating 60-75% until the systems are proven then 90%after that. Based on the current range of cost from $63-100 per acre, the value of labor savings and water conservation values on the test field are presented in the table below.

Test Field Yearly Irrigator Cost	**$63/AcYr**	**$100/AcYr**
90% Irrigator Cost Reduction	4309	6840
75% Irrigator Cost Reduction	3591	5700
60% Irrigator Cost Reduction	2873	4560
5% Conservation value	7147	7147
Total Labor Savings and Conservation Value		
90% Irrigator Cost Reduction	11443	14268
75% Irrigator Cost Reduction	10725	12834
60% Irrigator Cost Reduction	10007	11694
AutoFlood Payoff Years Combined Value		
90% Irrigator Cost Reduction	2.7	2.2
75% Irrigator Cost Reduction	2.8	2.4
60% Irrigator Cost Reduction	3.1	2.6
AutoFlood Payoff Years Labor Saving Only		
90% Irrigator Cost Reduction	7.2	4.5
75% Irrigator Cost Reduction	8.7	5.4
60% Irrigator Cost Reduction	10.8	6.8

CONCLUSION

The first field tests of AutoFlood on-farm flood irrigation control technology demonstrated that is does work and it will improve income while mitigating the personnel problems associated with manual irrigation control.

Value for water conservation and reducing labor through proven reliability of automation are the keys to payoff efficiency.

Good farming will never eliminate human management, but irrigation automation will improve water conservation and farming outcomes.

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MARKET-BASED WATER TRANSFERS IN CALIFORNIA: A 25-YEAR RETROSPECTIVE

Steve Macaulay, P.E.[1]

ABSTRACT

California's landmark Drought Emergency Water Bank was announced on February 15, 1991. This unprecedented market-based water transfer program was created to respond to emergency water supply conditions in California, in the fifth year of a severe drought.

Prior to 1991, short-term water transfers as a response to drought were largely a theoretical academic exercise of putting water supplies to their highest economic use. There was no real-world experience in use of this tool other than a few small trial programs supported by the California Department of Water Resources (DWR) in 1989 and 1990. Such transfers had strong support in economic theory, but there were concerns regarding whether a large-scale program could be implemented. In January 1991 the initial forecast of surface water supplies throughout much of California was for very low deliveries, in part due to the continued drawdown of storage in most of California's resources beginning in 1987.

Consistent with the theme of water shortages and drought for this conference, this paper provides a recap of the California drought water banks of 1991, 1992 and 1994, as well as a review of transfers from 1994 through 2015. This paper, as augmented by the presentation to be made at the conference, describes the wide range of policy and technical issues arising from real-world water transfer experiences, and how those issues have progressed over the past 25 years.

The author was part of the executive team within the California Department of Water Resources, and was the overall manager of the 1991 and 1992 drought water banks. He is a recognized expert in water transfers and regularly provides water transfer support to clients.

INTRODUCTION AND BACKGROUND

Physical and Legal Setting

California has a temperate Mediterranean climate and abundant water resources. It has a population of 38 million people, and more than 9 million acres of irrigated farmland. Roughly 2/3 of the population is in the southern part of the state, and 2/3 of the water resources in the northern part.

It rarely rains during summer months. Consequently large surface reservoirs have been developed to capture water during the wet months (November through April) for release in

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the dry months (May through October). California is fortunate to have natural “reservoirs” in the form of extensive groundwater basins and seasonal snow pack in the Sierra Nevada mountains. All of these water resources contribute to a diverse, large water resources mix. Figure 1 is a map showing California’s principal agricultural regions, river systems and water projects.

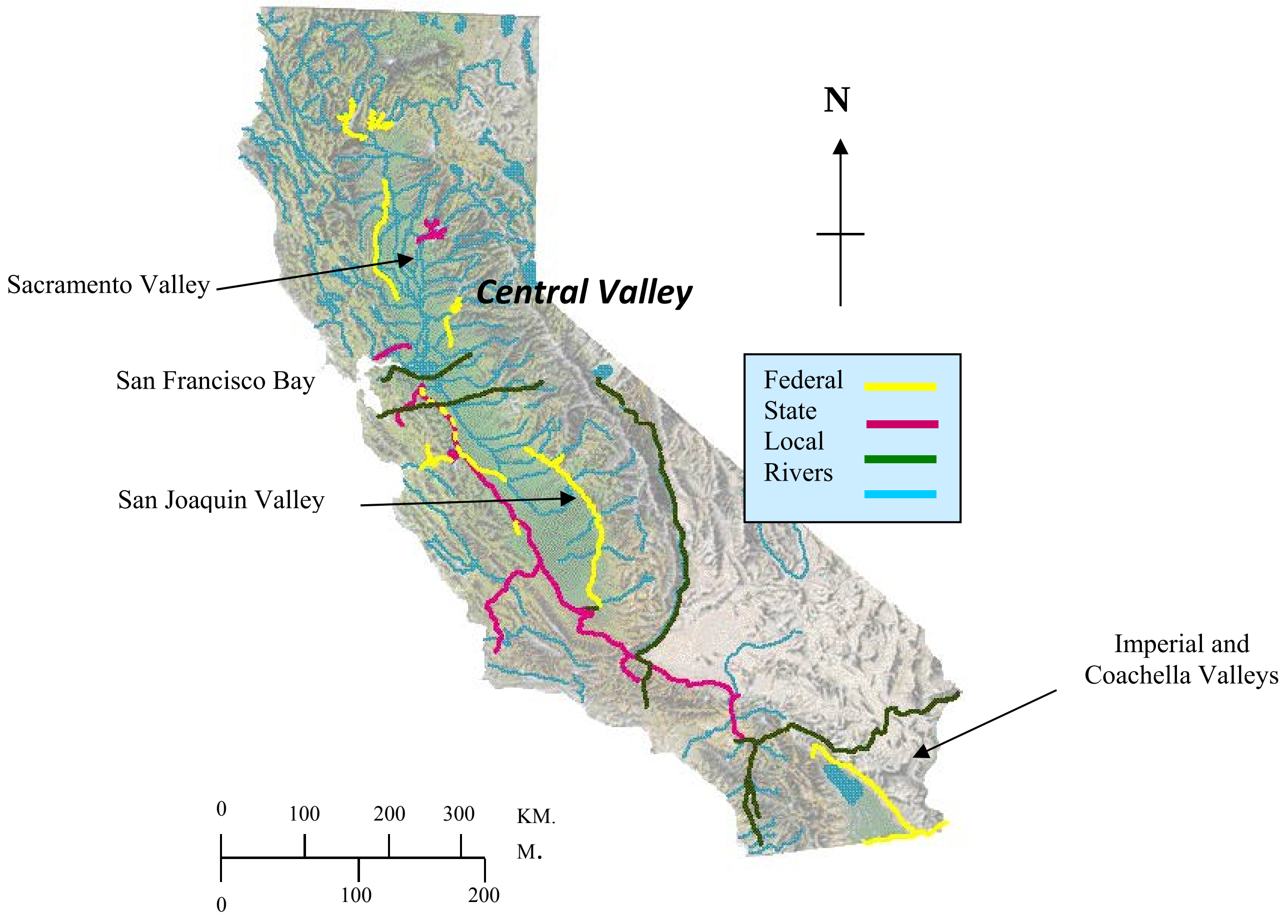

Figure 1. California River Systems and Water Projects, Principal Agricultural Areas

The Sacramento Valley is in the water-abundant north, and most of the region has ample water supplies in even the driest of years except for periods of extraordinary drought. There are more than 2 million acres of irrigated farmland. Return flows from irrigated agriculture are available for downstream users, and consequently water conservation measures are generally not considered for water supply reasons. A major crop is rice. The San Joaquin Valley has extensive productive farmland with a wide mix of crops. Agriculture benefits from local and imported surface water as well as extensive groundwater supplies. Overall, California has 9 million acres of irrigated lands.

Southern California is very dry, and most of the cities rely on water imported from Northern California and the Colorado River to the east. Cities near San Francisco Bay get their water supplies either directly from sources in the Central Valley or from reservoirs located in the Sierra Nevada on the east side of the Central Valley. Most water projects were originally designed to sustain a recurrence of the 1928 – 1934 historic drought. Northern California has adequate water supplies in most years, while the large population in Southern California is very susceptible to drought.

Much of California's developed surface water supplies are in the Central Valley, drained by the Sacramento River in the north and the San Joaquin River in the south. These two rivers join in the Sacramento-San Joaquin Delta (Delta) and flow into San Francisco Bay. The Delta is a tidal estuary where salinity is maintained by releases of fresh water from upstream reservoirs.

Several major water projects store water in reservoirs on these rivers, and divert water from the Delta. Salinity concentrations are managed at levels sufficient for both urban and agricultural uses in the export areas, as well as local uses in the Delta itself. Water is pumped from the Delta to other areas of California, including cities in the San Francisco Bay Area and Southern California. Water is also pumped to farms in the southern portion of the Central Valley.

California surface water rights were initially riparian and self-enforced. Towards the end of the 19th century appropriative water rights were added to the institutional framework, and such rights have been administered by state government since 1914. 100 years later the California Legislature developed, and Governor Jerry Brown signed the 2014 Sustainable Groundwater Management Act (SGMA). SGMA requires 127 medium and high priority groundwater basins in the state (representing more than 90 percent of California's population and irrigated farmland) to achieve sustainable conditions by 2040, with intermediate targets and requirements. Historic water transfers have been implemented through the regulatory environment as it has changed over the years, and SGMA is likely to change the future of water transfers even further.

1991, 1992 AND 1994 CALIFORNIA DROUGHT WATER BANKS

1991 – 1994 Experiences

The term "water transfers" is used in the context of market-based transactions (typically one year at a time) whereby a seller leases a portion of its water supplies to another user. Since the 1980s, California water law has allowed and encouraged water to be sold from one user to another, but there was very little practice of these market-based water transfers until 1991. The era of modern water transfers in California began with the 1991 State Emergency Drought Water Bank, a statewide water market administered by the California Department of Water Resources (DWR) in response to severe statewide water shortages in the fifth year of a continuing drought. This trial program did not directly connect sellers and buyers. Rather, DWR acted as an intermediate broker, acting as the buyer who then resold water supplies to water users who had demonstrated critical water needs as determined by DWR. Sellers had three sources: (1) water made available by fallowing land that would have been irrigated; (2) water made available by switching a portion of irrigation water supplies from surface to ground water; and (3) water released from local reservoirs that had been stored in earlier years. Prices were initially established based on the value of foregone irrigation supply benefits (set at $125 per acre-foot in 1991), but over time responded to market conditions of supply and demand. Sellers were unwilling to sell their water supplies less than the value they would have received from crop production, as well as less than what others might be receiving for an equal supply of water.

The Drought Water Bank was managed by DWR in cooperation with the USBR, and was staffed as an emergency effort (the author was manager of this program). The Drought Water Bank continued in 1992 and 1994, and provided substantial institutional experience for large-scale water transfers and marketing. More than 150,000 acres were fallowed during 1991[2], but none in 1992 and 1994 due to a combination of concerns regarding economic impacts of fallowing in selling regions as well as increased attention to water conservation by potential buyers. A number of presentations have been made on the California Drought Water Bank over the years at USCID conferences, with papers available in conference proceedings.

A summary of Drought Water Bank transactions from 1991 through 1994 is shown in Table 1[3].

Table 1. Drought Water Bank Purchases and Allocations
(1000 acre-feet)

	1991	**1992**	**1994**
Purchases	821	193 222	
Net Water Supplies	656	159 174	
Allocations			
Urban	307	39	24
Agricultural	83	95	150
Environmental	0	25	0
Carryover	266	0	0

Note that these are market-based transfers in addition to long-term transfers due to facility development and/or long-term agreements. For example, this does not reflect the long-term transfer agreements between Imperial Irrigation District and both the Metropolitan Water District of Southern California and San Diego County Water Authority, or the water transfers and exchanges that occur frequently among water users on the Sacramento River. The amounts varied from year to year due to changes in hydrology, as well as storage and water delivery conditions for the primary sources of long-term supplies.

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[2] California Department of Water Resources. The 1991 Drought Water Bank. 1992.

[3] Information taken from Table 2 in DWR report, Preparing for California's Next Drought, Changes Since 1987-1992, July 2000.

Key Issues

The 1991 Drought Water Bank was a large-scale experiment with the concept of market-based, short-term water transfers. Throughout 1991 the program was changed almost weekly as implementation problems were identified and experience gained.

Early in the 1991 program it became clear that not all the water savings from fallowing irrigated farmland would be realized, coupled with concerns over impacts of fallowing to the local economy. Issues raised regarding fallowing included:

1. Water savings needed to account for farming in low-lying lands. This was particularly a concern for the Sacramento-San Joaquin Delta, a 700,000-acre farming region at the confluence of the Sacramento and San Joaquin Rivers where much of the farmland is below sea level and sub-irrigation is a common practice.

2. Geographic variation in crop evapotranspiration due to cultural, weather and soil conditions. This became a predominant concern in future years and guided DWR's view of what crops to avoid in fallowing programs.

3. There was concern regarding "third party impacts" associated with fallowing (decreased farming investments such as labor, machinery purchases, tax revenues to support local government, etc.). This was difficult to quantify in 1991 due to an ongoing US-wide turndown in the agricultural economy, but there was a widespread view (particularly from local elected officials) that such impacts associated with Drought Water Bank fallowing were real. The mid-program response to this concern was to shift to other forms of transfers, with an emphasis on groundwater substitution.

4. In response to the issues of "third party impacts" as well as possible impacts from groundwater-related transfers, a number of counties adopted ordinances intended to insert additional local control over transfers.

5. The 1991 prices were relatively high ($175 per acre-foot) due to the dominance of fallowing. This dropped in 1992 and 1994 to around $70 per acre-foot due to the halting of fallowing as a water transfer source and the predominance of other sources.

Likewise, transfers related to groundwater substitution raised concerns about future impacts to flows in rivers and streams. While groundwater substitution transfers avoided "third party impacts" associated with fallowing, they were in a sense a borrowing against future water supplies. For the period 1991-1994 the presumption was that the magnitude of future impacts to water supplies were likely small as compared to the amount of water from such transfers to meet critical needs during the drought. Very little effort was put into understanding groundwater – surface water interaction resulting from such transfers due to the severity and immediacy of the drought. The primary focus of concern regarding additional groundwater pumping was selecting well locations and operations that: (1) minimized impacts to other local wells, and (2) avoided drawing water directly from rivers. Even so, problems with small wells going dry in one portion of the Sacramento Valley were attributed in the eyes of the local public as being associated with the Drought Water Bank programs.

1995 – 2015 MARKET-BASED WATER TRANSFERS

1995-2015 Experiences

While the drought ended in 1995, water transfers continued to play a role in helping to meet periodic water shortages. With only a few exceptions, most transfers from 1995 to the present have not involved DWR as an intermediate broker. However, DWR's operations of the California State Water Project (as well as the U.S. Bureau of Reclamation's Central Valley Project) have continued to provide conveyance capabilities to move water from sellers to buyers.

Table 2 shows the amount of water involved in north-to-south transfers from 1995 through 2015. This does not account for additional transfers that occur between water users in the same region, in part since such transactions do not necessarily require regulatory approval at the state level. As shown in Table 2, there are entries for "EWA" for the period 2001-2007. As a trial program, the "Environmental Water Account", which provided funding from state and federal governments for market-based water purchases to provide additional water above regulatory commitments. That trial program ended in 2007. Information from Table 2 is taken from a July 2015 report prepared by DWR and the California State Water Resources Control Board[4].

[4] Department of Water Resources and the State Water Resources Control Board. Background and Recent History of Water Transfers in California, Prepared for the Delta Stewardship Council. July 2015.

Table 2. Cross-Delta Transfer History, 1995–2015

Year	Without EWA	EWA	TOTAL
1995	0		0
1996	0		0
1997	0		0
1998	0		0
1999	0		0
2000	0		0
2001	298,806	105,000	403,806
2002	22,000	142,143	164,143
2003	0	69,914	69,914
2004	0	118,700	118,700
2005	0	6,044	6,044
2006	0	0	0
2007	0	125,000	125,000
2008	169,186		169,186
2009	274,551		274,551
2010	264,165		264,165
2011	0		0
2012	84,781		84,781
2013	351,515*		351,515*
2014	414,629*		414,629*
2015	262,466*		262,466*

*Preliminary data

While there are various conditions and limitations related to conveyance losses in the years represented in Table 2, there are several important observations. First, there were a number of years in which there were no transfers, and this was due to very wet conditions. Second, the magnitude of transfers has changed from year to year, driven by the adequacy of base water supplies by the buyers as such base supplies changed from year to year. Third, even the preliminary numbers for 2013-2015 are fairly large compared to other years. This represents a drought period that began in 2012 and may continue through at least 2016 depending on reservoir storage recovery during the winter and spring of 2016.

Addressing Issues Associated with Transfers

The 1991 Drought Water Bank contracted for more than 800,000 acre-feet of water, but the actual "new water" made available through these contracts was substantially less due to a combination of factors including early mistakes/misunderstandings and transportation losses. Table 1 shows purchases from sellers of 821,000 acre-feet, with net water supplies of 656,000 acre-feet. In fact, there were concerns as of the end of 1991 that the true net amount of water was even less. This has factored into changes in water transfer rules and policies following the 1991, 1992 and 1994 Drought Water Banks.

As described in the DWR and SWRCB 2015 report, there has been an evolution in the general understanding of how much water can be made available from various types of transfers, as well as potential impacts associated with large-scale transfers from a single region.

For at least the past decade DWR has maintained a draft "white paper" that provides guidance for each year on what they view as acceptable technical support for each category of water transfer. Fallowing guidelines have changed substantially since the experience during 1991-1994 -- some crops are no longer accepted since the crop water savings for such crops is not uniform over geographic areas and irrigation practices. In the case of groundwater substitution transfers, they are subject to "loss factors" related to potential future year impacts on groundwater basin storage. Both of these restrictions have continued to change as greater experience and technical understanding is gained. DWR continues to support a common set of guidelines that are applied to transfers regardless of geographic locations, with few if any exceptions considered due to local circumstances. While this has proven to be frustrating for some sellers, it responds to DWR's concerns that it acts on transfer proposals in a timely manner. Case-by-case considerations of water transfer proposals during drought conditions has proven to be very difficult due to the combined factors of the large number of transfer activities and the need to make decisions as early in each year as possible.

In addition, a number of important changes in federal and state law and regulatory actions have affected the California water market. Passage of the federal Central Valley Project Improvement Act in 1992 (PL 102-575) reallocated 800,000 acre-feet per year from agricultural and urban water users to environmental uses. This has had the impact of increasing the demand for supplemental water, but also may have limited water available for sale. Increasing regulatory restrictions under the federal and state endangered species acts have also increased supplemental water demand and likely decreased available supplies. In addition, such restrictions have seriously restricted the time of year and available capacity to transport water from sellers to buyers. All in all, regulatory restrictions have greatly affected the water market to the extent it seems far less predictable than it did in the 1990s.

2014 SUSTAINABLE GROUNDWATER MANAGEMENT ACT — A GAME-CHANGER

Several recent USCID conferences have put more attention on groundwater, particularly with the new law in California that requires sustainable groundwater management throughout the state by 2040. In particular, the June 2015 USCID conference in Reno included a number of presentations and papers describing the 2014 Sustainable Groundwater Management Act (SGMA). SGMA has entered its second year of implementation, and there will be several presentations at the May 2016 USCID conference on this topic.

In order to get to sustainable groundwater basin management, the most challenged basins (those in long-term overdraft such as the large agricultural region of the San Joaquin

Valley) will need to reduce groundwater pumping over the next 20 years, in addition to moving forward with options to increase replenishment of water in each groundwater basin that is not in balance.

SGMA is expected to have impacts on water transfers in at least two ways. First, transfers that are based on groundwater substitution will be subject to greater scrutiny by water managers in selling regions. Such transfers will likely need to be evaluated in the context of potential impacts on the long-term water balance of such basins. This may have the greatest impact in the Sacramento Valley, a frequent source of water transfers employing groundwater substitution. A second impact is likely to be an increase on the "demand" side as groundwater basins that are currently in overdraft seek new water supplies to replenish their aquifers. It is premature to reach any conclusions on the impacts of SGMA, but it will be worth following and is likely to change both supplies and demands over the next 20 years.

WATER TRANSFERS FOR THE FUTURE

Over the past 25 years, annual and multi-year water transfers have substantially added to water supply reliability for a number of irrigation and urban water interests. As economists identified in the 1980s, there is an economic attraction to market mechanisms allowing for transfer of water from lower value farming uses to higher value farming and urban uses during drought periods, when regular water supplies are typically short. At the same time, such transfers can provide substantial economic benefits to sellers. In addition, DWR moved out of its brokering role following the 1987-1994 drought as both sellers and buyers gained experience in putting their own transactions together.

A number of legal and other constraints have been put in place to reduce or avoid impacts to the local economies of selling regions, as well as addressing unintended impacts to overall future water supplies. At the same time, dry-year transfers have become increasingly important for several reasons:

1. Impacts of climate change threaten to reduce California snowpack, with predicted reductions in water supply reliability for many water users. Combined with other factors listed below, this could have the impact of increasing the period of time for water shortages.

2. There has been a substantial investment in higher-value permanent crops, particularly almonds and walnuts. This is putting increased pressures on reliability of irrigation water supplies during dry years and drought periods.

3. For whatever reasons, there have been greater drought periods since the late 1980s than California experienced through much of the 20th century.

4. Despite extraordinary water conservation measures implemented beginning in 2014 by state government, California's population continues to increase.

5. An increasing concern during recent severe droughts about meeting minimum health and safety needs in both urban and rural populations.

6. The implementation of SGMA will require greater attention to long-term groundwater basin water balances, which will be affected by potential water transfers. To get into balance, some groundwater basins will need to recharge more water supplies, which could be available through wet-year water transfers (this will be in addition to considerations of reducing groundwater pumping demands).

With the passage and implementation of SGMA and much greater attention to a broad spectrum of water issues brought about in part to the continuing drought that began in 2012, it is appropriate to consider how market-based water transfers will fit into California's water future. It is possible (personal communication, DWR Deputy Director Gary Bardini, February 5, 2016) that some changes will be coming to how water transfers are administered. This could include more attention to water transfers within groundwater basins, some form of a state "water bank" to assure that minimum health and safety needs will be met during extreme drought conditions, and renewed attention to water transfers for environmental purposes. What will not change are the pressures for DWR – as California's technical overseer and de-facto regulator of the water transfers market – to make quick decisions in the uncertain environment of severe droughts and a changing regulatory landscape.

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FUNDING PLACE-BASED PLANNING FOR WATER RESOURCES IN OREGON: A NEW APPROACH

Laura Ann Schroeder[1]

ABSTRACT

In August 2012, the Oregon Water Resources Commission adopted Oregon's first Integrated Water Resources Strategy (IWRS). This strategy contained more than 40 recommended actions, one of which was to encourage communities to take place-based and integrated approaches to water resources planning. The goal of place-based planning is to provide support for Oregon communities in order to allow communities to identify their water resources needs and partner with agencies to develop solutions and projects to help communities meet those needs now and into the future.

In February 2015, OWRD released place-based planning guidelines. In July 2015, the Oregon Legislature allocated additional staff as well as $750,000 to pilot the approach. In December 2015, the Oregon Water Resources Department (OWRD) had received sixteen letters of interest from across the State. OWRD suggested funding 4 pilots at the February 2016 meeting. This paper explores the background to this innovative program and the proposed guidelines. Additionally, it describes the proposed projects and offers insight into additional opportunities for communities to engage in solution driven approaches.

INTRODUCTION

Water crosses political boundaries and connects vastly different landscapes. In Oregon, even where water is in apparent abundance for much of the year, it is exceedingly difficult to address water-related challenges through a piecemeal, uncoordinated approach. In a changing climate, without addressing water-related challenges across the state, the quality of life for Oregonians will be impaired and communities will be unable to reach their economic, social, and environmental potential.

In 2009, the Oregon Legislature passed House Bill 3369[1], which directed OWRD to develop a statewide Integrated Water Resources Strategy (IWRS) to help Oregon meet future water quantity, water quality, and ecosystem needs. OWRD was instructed to develop a strategy to implement a coordinated, integrated state resources policy and provides means for its enforcement as authorized under ORS 536.220.

In August 2012, the Oregon Water Resources Commission adopted the state's first IWRS, which provided a blueprint to help the state better understand and meet its instream and out-of-stream needs.[2] As part of its recommendation, the OWRD

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recommended that it assist communities undertake an integrated, place-based approach to water planning. OWRD envisioned place-based integrate water resources planning to be a voluntary, locally initiated, and locally lead effort in which a balanced representation of water interests with in a specific basin, watershed, or groundwater area would work in partnership with the state to:

- Build a collaborative and integrated water planning process
- Characterize current water resources and issues
- Understand current and future instream and out-of-stream water needs
- Identify and prioritize strategic solutions to meet current and future water needs
- Develop a place-based integrated water resource plan that informs the IWRS[3]

Plans were intended to account for interaction between ground and surface water as well as delineate and describe local population centers, key industries, and listed fish species, among the many other factors that influence the use and management of water.

The 2015 Legislature passed additional legislation refining the definition of place-based integrated water resources as referring to waters that are from sources within a single drainage basin or within an area that is a subset of a single drainage basin.[4] The legislation further provided that OWRD could issue grants from available moneys to facilitate the preparation of place-based integrated water resource strategies that are consistent with state laws.

Thus, the place-based planning guidelines utilize a holistic and coordinated approach in order to allow partners to work together to create a vision for their community's water resources. Each step in designed to create collective buy-in and foster communication among different entities and water users. Together with existing law, regulations, plans and program this voluntary program is designed to bring existing resources together in a strategic way in order to provide opportunities for coordination, funding, and ultimately progress.

PLACE-BASED PLANNING GUIDELINES

The guidelines are composed of five steps. In order to be considered a place-based plan that facilitates coordination of the statewide Integrated Water Resources Strategy, planning groups must adhere to the planning guidelines.

The first step of the guidelines is to build a collaborative and integrated process.[5] The guidelines indicate planning groups have the flexibility to establish their own geographic planning scale but recommend looking to the administrative drainage basins identified in OAR Chapter 690, Divisions 500-520 as a starting point.[6] The first step stresses that the Convener, whomever is chosen, should be a person that is highly respected and has a reputation for serving the public interest.[7] The first step also stresses the importance of involving agencies as partners as well as other diverse interests including local governments, tribal governments, municipal and wastewater utilities, major industries, agriculture, forestry, environmental groups, small businesses, private landowners and state and federal agencies.[8] Lastly, the first step of the guidelines stresses the importance of creating a transparent and inclusive process.[9] This includes publicizing and accepting public comment at each meeting and complying with the state's Public Meetings Law.[10]

The second step of the guidelines involves characterizing the water resources, water quality and ecological issues of the established geographic planning scale.[11] The purpose of this step is to help the planning partners collectively identify challenges currently facing the community and start mapping potential opportunities to address any water quantity, quality or ecological issues.[12] This step is also designed to create an opportunity to tell the story of what makes the geographic planning area unique.[13] The place-based plan should describe existing basin programs, policies, and classifications, and any other legal protections when characterizing water resource issues.[14] Additionally, the place-based plan should describe surface and groundwater resource availability and quality.[15] Lastly, the plan should include a general description of the ecological health of the planning area including a description of key species and habitats, the historical and current presence of aquatic species, including any listed species, and a discussion of limiting factors that affect aquatic habitats in the planning area.[16]

The third step of the guidelines is to quantify existing and future needs and demands of the planning areas water resources.[17] This step is designed to identify how much water is needed to support current and future uses of water, to examine when and where supplies do not meet out-of-stream or instream needs and demands today and determine where existing supplies are likely to fall short in the future.[18] Planning groups are instructed to use a 50-year planning horizon and account for future pressures such as climate change, population growth, and land-use changes.[19] Groups are encouraged to look to other plans where this information may have already been quantified such as in municipal water management plans, TMDL plans, habitat restoration plans, forest management plans, and conservation and species recovery plans.[20] Lastly, planning groups are asked to identify where conflicts among uses are most likely to arise in the future.[21]

The fourth step involves developing integrated solutions for meeting long-term water needs.[22] During this step, planning groups will likely need to consider a suite of tools, and examine various options for meeting unmet needs and demands.[23] Solutions can include existing practices, but groups are instructed to look to improving efficiency and implementing conservation measures, examining built and natural storage, utilizing water rights transfers and rotation agreements, creating non-traditional water supply techniques such as rainwater recapture, storm water capture, greywater and desalination, and maintaining current infrastructure and developing new infrastructure where needed.[24] The fourth step also explains that planning group will need to consider actions to improve and maintain ecological health of the planning area, protect instream flows, improve water quality, and expand monitoring efforts.[25]

The fifth step involves plan adoption and implementation.[26] The guidelines explain that a place-based plan should be completed within a reasonable time frame, approximately three years from initiating the planning process. Once planning members formally approve their plan, the OWRD, working with Oregon Department of Environmental Quality, Oregon Department of Fish and Wildlife, and the Oregon Department of Agriculture will conduct an inter-agency review of each place-based plan and make a decision about accepting the plan as a component of the Integrated Water Resources Strategy.[27] Implementation of the plan will involve various partners and result in a suite of projects and programs which will require a more detailed implementation strategy, agreement, or work plan.[28]

FUNDED PROJECTS

In July 2015, the Legislation provided funding and staff to OWRD so that it could assist communities undertake place-based integrated water resources planning. OWRD received $750,000 to distribute in the form of grants to support pilot programs. Letters of interest were solicited from communities.[29]

At the February 2016 Commission meeting, OWRD approved a limited number of grants awards to fund pilot place-based integrated water resources planning programs. Communities that submitted letters of interest were evaluated against a set of review factors that included evaluation of the strengths and weakness of the proposals in terms of leadership, partnerships, capacity, integration, planning needs and outcomes, approach, need for assistance, readiness, and likelihood of developing a plan within a two- to three-year period. Additionally, factors that would allow for testing place-based planning in places with different characteristic were taken into consideration including geography, scale, type of convener, local capacity, proposed approach and backgrounds in water planning and collaborative planning.[30]

Out of 16 proposed projects, four projects have been suggested to receive funding from OWRD.[31] Two projects, the Upper Grande Ronde Watershed and the Lower John Day Partnership were recommended for full funding.[32] Two additional projects, proposed by the Mid-Coast Basin Planning Group and the Harney County Watershed Council were recommended for partial funding.[33] In total, the recommended funding reaches $657,000, with the remaining suggested to be held in reserve to assist in smaller grants relating to building a collaborative and integrated process for the existing pool of proposals.[34]

Upper Grande Ronde Watershed Planning Group

The Upper Grande Ronde River Watershed place-based integrated water resources planning grant proposes to develop a collaborative effort among a balanced representation of local organizations that have a vested interest in the area's water resources.[35] The overarching goal for this planning group is to evaluate all the demands on the water resources within the watershed and compare that demand to the available water resources.[36]

Focusing the planning area in the Upper Grande Ronde River Watershed, which closely aligns with the boundary of Union County, Convener and Union County Commissioner, Mark Davidson, has identified partners from three major water resource demand groups: agricultural, municipal and ecological.[37] Using input from these key project partners as well as other local input, the planning group shall utilize its funding to synthesize the significant body of research on water quality, quantity, and ecological demands in the watershed in order to develop a seasonal-level analysis to evaluate whether the demands are aligned with the available water quality and quantity.[38]

Once data is analyzed to evaluate availability, that information will be used to develop strategies to balance water demand with supply.[39] These strategies might involve improving water storage, conveyance, treatment, and reuse and include evaluating on a watershed scale, water resource management strategies to meet demands and improve efficiency.[40] The final outcome is to develop a document that can serve as a roadmap to align demands with available resources and identify key projects for further development.[41]

John Day Basin Partnership

The John Day Basin Partnership takes a slightly different approach than the Upper Grande Ronde Watershed. The focus on this planning area is in the Lower John Day Sub-basin. This basin occupies 44% of the John Day River Basin.[42] The area is heavily reliant on agricultural production based on livestock and dryland wheat and growth in these areas is difficult due to a lack of water storage and infrastructure.[43] Prolonged drought and climate change indicate that water availability will continue to be an urgent issue in the region.[44]

The John Day Basin Partnership, the convener, was originally formed in 2014 to accelerate the pace, scale, and impact of watershed restoration across the basin.[45] The anticipated results of this partnership involve both short-term and long-term outcomes.[46] The short term outcomes anticipated involve obtaining a balanced representation of water interests engaged in the place-based planning effort, a clear understanding of current and future water demand, a plan that addresses pressing water quantity, quality and ecosystem health, work to identify a suite of attainable, measureable, and locally acceptable water projects that are immediately actionable, and a process to monitor and adapt the plan as needed.[47] The long term outcomes anticipated involve obtaining a more sustainable balance between water supply and demand for the next generation of water users; increasing water reliant economic development; creating safe migration corridors and resilient habitat; and improving the function of headwater meadows and floodplain processes.[48]

Mid Coast Basin Planning Group

The Mid-Coast Planning Group is convened by the City of Newport and the Oregon Water Resources Department.[49] This group proposed to study the water supply and demand needs within the Lower Siletz, Lower Yaquina, and Devils Lake-Moolack Frontal Watersheds.[50] The area is characterized by several competing interests including out-of-stream needs for municipal drinking water, agriculture and industrial use and in-stream needs to sustain the Basin's diverse aquatic species, water related tourism and commercial, recreational, and tribal fisheries.[51]

The primary goals of this planning study include: 1) Engaging a diverse set of stakeholders within the Mid-Coast Basin in order to understand and characterize the water resources in the area; 2) collaboratively identify current and future in-stream and out-of-stream water supply needs and demands; 3) collaboratively develop and prioritize options to respond to identified imbalances; and 4) develop an integrated water resources plan to inform long-term planning and support regional strategies for addressing watershed challenged in the Mid-Coast Basin.[52]

Malheur Lake Place-Based Planning Group

The Harney County Watershed Council is acting as the convener for this Planning Group. Harney County has been reporting declines in ground water levels for several years.[53] Last spring, OWRD placed a moratorium on new and pending groundwater applications within a major portion of the basin.[54] Moreover, Governor Kate Brown has declared an exceptional drought emergency exists in the County.[55] Thus, with water being at the center of ecological, economic, and human health, placed-based planning can help identify community supported projects, help coordinate resources and implement projects to benefit diverse interests.

The primary goals of this place-based plan involve collecting science-based information regarding water resources to create a foundation to initiate collaborative planning, foster collective agreed upon direction and tangible strategies for integrated water management, and lastly, developing an actionable, fundable and well-supported integrated water resources plan in order to ensure sustainable water resources for the economic drivers of the area.[56]

OPPORTUNITIES

Each proposed planning group has identified critical issues relating to water resources in its planning area. By working to create local collaborative groups where water resource issues can candidly be discussed and solutions brought forward, Oregon is leading the way in allowing its communities to develop innovative place-based solutions to pressing water needs. Nevertheless, this pilot project is only able to fully fund two proposals and partially fund two others. If Oregon is going to make meaningful strides across the State in working to develop collaborative solutions to water issues, additional funding that is reliable and sustainable over the entire planning horizon is critical.

In addition to providing additional and long-term funding, the State should explore securing financing for proposed projects and helping to provide technical expertise to communities planning proposed projects. Grants for technical expertise for developing water storage and infrastructure could be especially helpful in areas where drought hinders both economic development and ecological resilience. Moreover, grant programs that provide for transaction support for things such as water rights transfers, surface water and ground water exchanges, and developing water markets will provide additional resources that communities can leverage in both the short and long term to reach their water resource management goals.

CONCLUSION

Oregon is looking to innovative and place-based solutions in the face of ongoing drought, population growth, increasing demands on natural resources, and climate change. By providing funding for place-based planning, communities will be empowered to inform themselves about available resources and take steps to ensure they are sustainably managed. Nevertheless, continued funding and technical expertise will be critical for providing ongoing support as projects develop and begin to be implemented.

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CONTROLLING SALT PROBLEMS ON THE SAN JOAQUIN RIVER

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ABSTRACT

The San Joaquin River is the largest river of Central California. The 366-mile long river starts in the high Sierra Nevada at an elevation of 9,839 Ft, and flows through the rich agricultural region known as the San Joaquin Valley before reaching the Bay-Delta, and Pacific Ocean. The San Joaquin River is among the most heavily dammed and diverted of California's rivers.

The Grassland Water District (GWD), salt monitoring and management pilot project is part of a Basin-wide effort to implement real-time salinity management as a more cost-effective alternative to TMDL-based salinity management. The GWD pilot project focuses on the management of seasonal wetland drainage of elevated salinity to the San Joaquin River. The project aims to develop a functional sensor network with real-time data management providing an exemplar for other wetland and agricultural drainage entities in the Basin.

The initial phase of the project has involved design of a Water Information Management System (WIMS) that will provide a software and hardware solution for collecting, managing, evaluating and automatically correcting water quality data. Once the WIMS is fully operational it will provide a higher quality of data that can be utilized by water quality forecasting models of the San Joaquin River and its associated watersheds, helping improve scheduling of saline drainage from wetland and agricultural sources to the San Joaquin River.

Future goals will be to share the real-time data with the Basin stake holders so as to minimize calls on east-side reservoirs to provide dilution when water quality objectives at the Vernalis compliance station are exceeded.

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Figure 1. San Joaquin River basin

INTRODUCTION: SAN JOAQUIN RIVER

The San Joaquin River (SJR) is the largest river of central California. Its head waters originate high in the Sierra Nevada Mountains, elevation 9,839 Ft-MSL. Flowing due west past Fresno, California, then entering the San Joaquin Valley where it turns north toward the San Francisco Bay Delta, then out to the Pacific Ocean.

With a basin size of 32,000 square miles and a river length of 330 miles the majority of the channel cuts through the rich farm land of the San Joaquin Valley. Once the richest river ecosystem in California, now polluted where it runs through the valley.

The Real Time Management Program (RTMP) was initiated in 2004 as a long-term, innovative plan to meet the salinity objectives at Vernalis compliance monitoring station of the San Joaquin River through the cooperation of basin stakeholders and coordination of their efforts to manage salt loading. The RTMP helps to maximize the salt exports in the Lower San Joaquin River while maintaining compliance with salinity water quality objectives defined at Vernalis. The RTMP real-time load allocations replaces the monthly salt load allocations specified in the 2004 TMDL and existing Water Quality Basin Plan for the San Joaquin River Basin.

The California Department of Water Resources (DWR) and the US Geological Survey (USGS) operate flow and water quality monitoring stations along the SJR and its tributaries. These stations and others provide real-time input data to the models that are used to forecast flow and water quality at specified compliance locations along the river. This will allow basin managers to coordinate drainage flows and the Eastside reservoir operations to meet the salinity compliance objectives at Vernalis once the sensor network within the Basin has been fully enhanced and data sharing protocols have been established.

Under a real-time management program salts are only discharged from east and west-side watersheds while there is assimilative capacity in the River, rather than be constrained by mandated (and more conservative) monthly load allocations. Managing the use of assimilative capacity is anticipated to reduce reliance on fresh water releases from New Melones Reservoir that typically are made to assist in meeting salinity objectives at Vernalis during dry and critically dry years.

RTMP AREA OF FOCUS

Real-time salinity management has been written into the Basin Water Quality Plan for the San Joaquin River Basin and is the most cost-effective long-term solution to salinity problems within the Basin which balances the dual objectives of maximizing out-of-basin salt export while maintaining compliance with a strict 30-day rolling average salinity objectives set independently for summer and winter periods. The summer objective of 700 uS/cm is protective of downstream irrigated agriculture where water supplies are diverted directly from the San Joaquin River. The winter objective of 1,000 uS./cm is higher – since the limiting agricultural beneficial use if not constraining during the winter (non-irrigation) season. The proposed solution or mechanism to meet and maintain water quality in the San Joaquin River as stated in the RTMP is:

1. Develop a fully functional and comprehensive sensor network of flow and EC monitoring stations.
2. Develop IT capability to allow data collection, management and sharing of this data basin-wide in real-time.
3. Calibrate and improve the accuracy of existing San Joaquin River and watershed computer-based models to produce two week forecasts of San Joaquin River assimilative capacity as measured at the Vernalis compliance monitoring station.
4. Work with basin stakeholders to improve salt management and control capabilities to schedule west-side salt loading during period of sufficient San Joaquin River assimilative capacity.

Additional strategies might be to limit the loading of salt via the Delta Mendota Canal, the main source of agricultural and wetland supply water from the Delta. Controlling salt load imported to the Basin is considered a separate issue. The remaining portion of this paper will be focused on the monitoring and management of the salt load that is discharged to the San Joaquin River from west side sources to coincide with forecast flows from the East side reservoirs to meet water quality objectives.

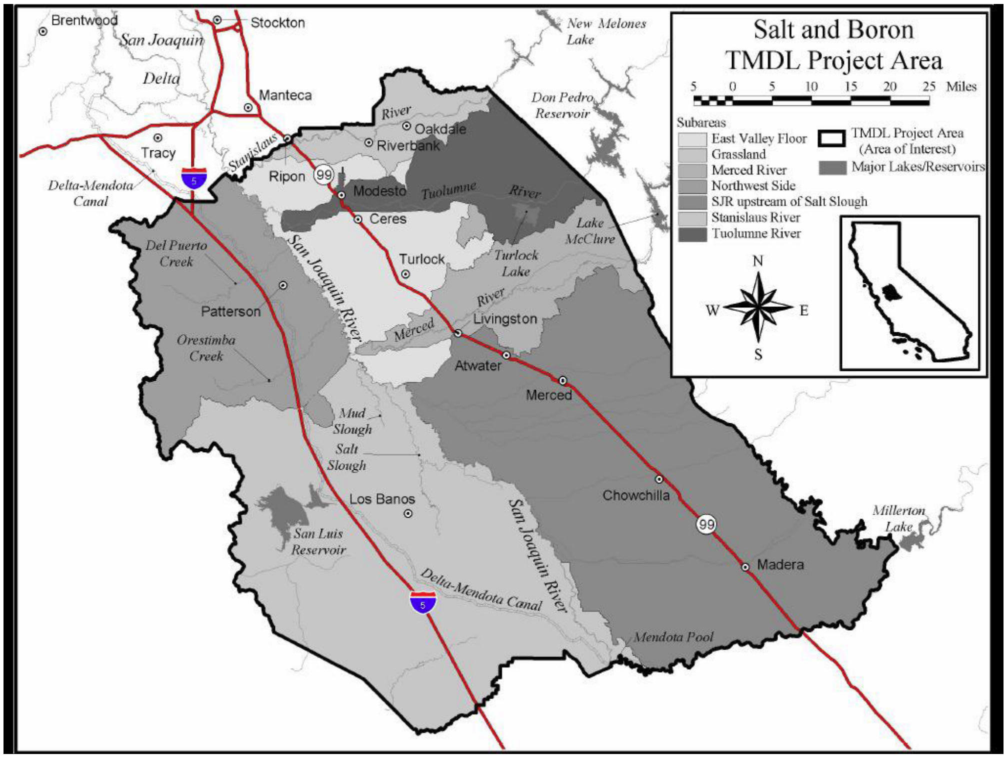

Figure 2. San Joaquin River basin study area

GRASSLAND WATER DISTRICT PILOT PROJECT

Several State and Federal grants were awarded to Grassland Water District and Berkeley National Laboratory which allowed the development of a sensor network of 50 flow and salinity monitoring stations. Grassland Water District is a water purveyor on the west-side of the San Joaquin Basin serving 160 individual duck clubs and land and cattle operations within an area of approximately 51,700 acres. Hardware vendors were selected and equipment deployed (YSI-ECONET) that allowed automated collection and transmission of continuous data to a remote server where it was managed and presented on a hosted web site, provided by the sensor hardware vendor. The overarching goal of these pilot projects was to determine the potential benefits and environmental impacts of local district level management saline wetland drainage to the San Joaquin River.

One of the oversights of the YSI-ECONET system selected by the project team for deployment in the District was the inability to perform data quality assurance in real-time or, at the very least, on a daily basis that would allow development of real-time drainage salt load forecasts to coincide with daily San Joaquin River assimilative capacity forecasts. This also had the effect of limiting that type of data sharing between stakeholders that was considered essential for Basin-scale real-time salinity management.

Further, the project team determined that the software solution ought to be a Commercially Available Off the Shelf product, with the ability to apply business rules specific to the districts data needs to automatically validate, correct, present the data in graphical form, and visualization with web solutions. Ideally, the software solution would be a product that had previously been adopted by other water districts. This had two advantages: (1) water districts tend to adopt technologies more readily when used by sister water districts; (2) data sharing and information exchange between water district stakeholders is facilitated when water districts share the same software technology. Since real-time salinity management is ostensibly about data sharing allowing west-side drainage salt loads to be matched with east-side reservoir releases that generate salt assimilative capacity - real-time data quality assurance is an essential requirement for a successful long-term solution.

The project team acquired the KISTERS' WISKI hydrological data management software and over the next two years worked closely with the company to develop the data management platform and associated tools to allow monitoring site data to be simultaneously reported to the YSI ECONET server as well as a local database housed at the District. The long-term goal was to develop capability to allow a stable and robust data management system to be developed that would allow migration from YSI-ECONET with the subsequent savings of over $30,000 annually in cellular service fees and software maintenance.

The product manager requested that the KISTERS team participate in the pilot supporting the software and assisting the district with installing and configuring the software. Once the web solution has been finalized and implemented and new hardware installed within the District to migrate a mixed cellular/RF radio system to a mostly RF system with a base station located within the District headquarters, the project will be successfully completed. The incremental deployment strategy that was adopted by the project team has allowed local wetland managers to evolve at a manageable pace in their embrace of the technology. In so doing they have developed a more quantitative approach to wetland water management.

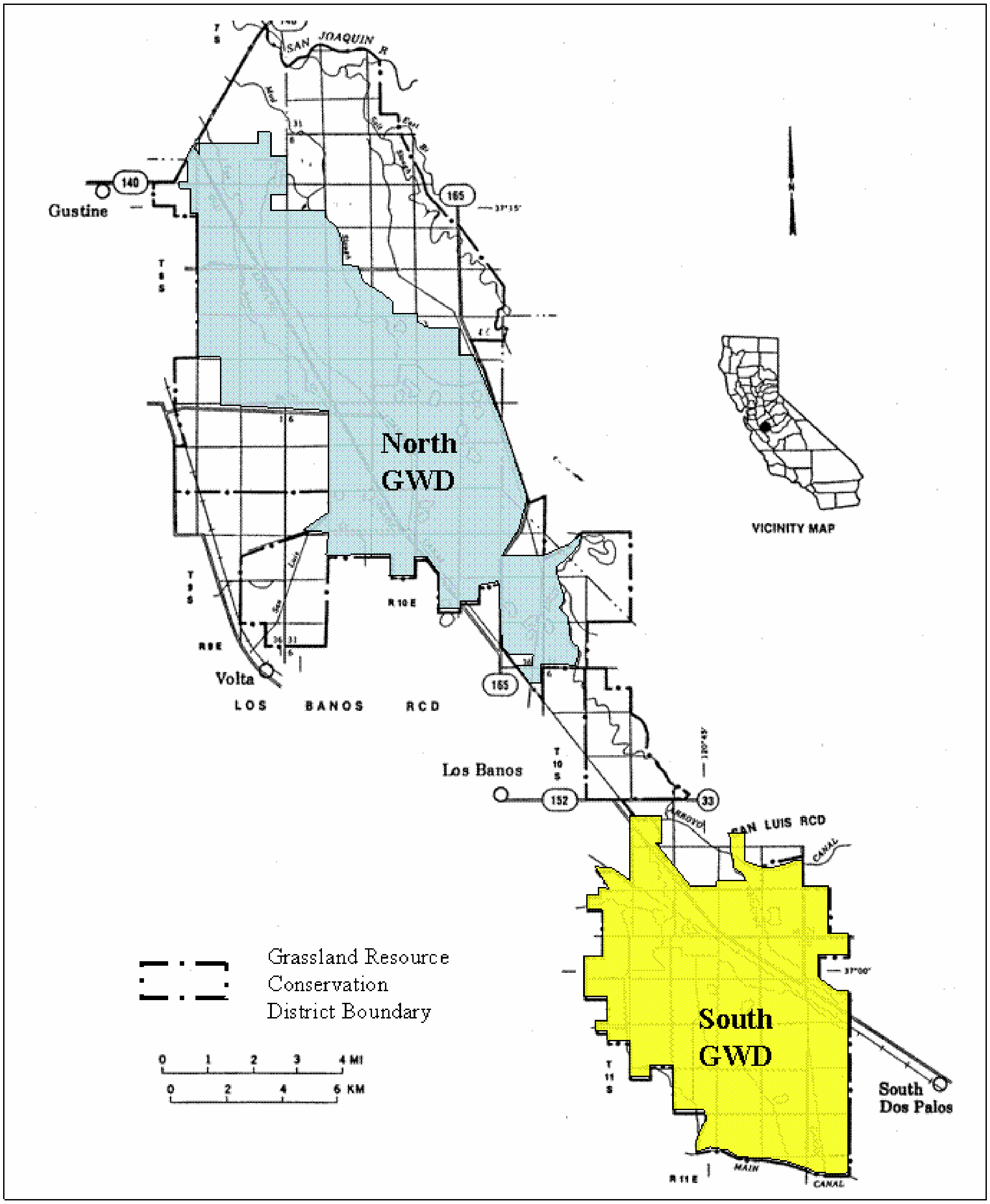

Figure 3. Grassland Water District Project Area

WHY WAS A WIMS SELECTED OVER A SOLUTION SUCH AS SCADA?

The constant changing conditions and dynamic state of the data stream necessary for monitoring, managing flows, and computing salt concentration in drains and the San Joaquin River required a real-time data management solution. Real-time data management is usually reserved for solutions such as SCADA (Supervisory Control and Data Acquisition). However, SCADA is most often associated with the collection and presentation of current conditions so that appropriate changes may be made to insure the smooth operation of a facility.

The use of the term “Real-Time Data” is often misleading in its use. Real-Time Data (RTD) refers to data that is collected at a frequency rate typically sub minute and delivered immediately after collection. Primarily reserved for SCADA applications. This type of solution is necessary to allow operators to manage facilities such as hydroelectric generating stations, waste water plants etc. in real time.

Near Real-Time Data (NRTD) refers to data that is collected in intervals of 5, 15, 30 minute or greater intervals and delivered at the collection rate or greater depending upon telemetry cost, power management and needs of the data users.

The use of data for decision support, presentation, management and modeling requires the best or highest quality data available. This can be difficult and labor intensive especially if there are large quantities of data imported at a high frequency.

Data being collected by monitoring station sensors requires frequent ongoing maintenance and calibration. Raw data quite often are plagued with fly outs, dropouts, and missing data but yet this data is used to make decisions on a weekly, daily or hourly basis. An automated method of scrubbing this data is necessary for a real-time decision support system. This is where KISTERS line of data management solutions come in to play.

APPLYING BUSINESS RULES TO DATA FOR USE IN REAL-TIME

Without oversight and evaluation it becomes extremely difficult for an organization such as a water district to use their data to make informed decisions. Data that does not conform to a reasonable standard of quality is not dependable and should not be used for decision making purposes. KISTERS’ Water Information Management Solutions data evaluation tools, when combined into business rules can automatically apply data evaluation in near real time and supply the user with the highest quality of data available based on the incoming raw data sets.

The design of business rules for data management are specific to the type of data collected and the intended use of the data. Typical problems with data are:

> Missing – The business rule for missing data can be as simple as missing with no attempt to fill in the gap. However, if you have a model that uses Time Series Data for its forecasting needs and a null value is not acceptable then something must be done to fill the gap. If a one hour model is run and you have missing data for longer than an hour then the forecast result is missing. Missing data can be managed automatically in a number of ways depending upon the data gap. If the data is predictable and the period of missing data falls within an acceptable time period such as four missing values in a single hour of 15 minute data, it could be acceptable to

just fill the gap with linear interpolation. However, this level of data validation must be approved by the users of the data or the authority of the data.

Spikes and dropouts – The business rules for spikes and dropouts depend upon the severity of the spike and dropout. Water quality data is notorious for spiking and dropping out. Data that is normally in the range of 1,000 units and spikes to 7,000 units is somewhat easy to manage depending on the length of period of the spike. This is true with dropouts as well. With water quality data, acceptable min and max limits are usually well understood for the reach being monitored. Threshold values can be developed for these values to clip the data to the reasonable limit. A dropout that cannot fall below the value of zero can have a rule that clips the data if it is less than zero. Spikes and dropouts with lessor magnitudes are more difficult to detect and therefore correct, but it can be done. Business rules for spikes and dropouts in this category require testing over time with large data sets to insure they fall within the reasonable limits of the data.

Business rules used for the correction of noisy data can make the difference between meeting and not meeting compliance. Either when using models to provide forecasts for managers to increase or decrease flows from New Melones or water districts to open or close gates managing the water releases to the San Joaquin River.

EXAMPLES OF BUSINESS RULES BEING APPLIED TO NOISY DATA ON THE SAN JOAQUIN RIVER

The following examples of the use of the WISKI database solution by the Project Team at GWD and LBNL are data that has been chosen from one of the agency-supported stations along the San Joaquin River. Data from these stations are posted every 15 minutes to the California Data Exchange (CDEC). The data is then automatically downloaded and imported into WISKI as soon as it is made available by CDEC.

The first example Station is the San Joaquin River at Maze Blvd (MRB). Figure 4, shows the data plagued with spikes and dropouts. The data has had a simple business rule applied, clip all data less than zero. This is a simple rule that can be applied to all data that cannot drop below zero. Notice the large spike that extends from an average of 1,000 units to over 40,000 units. This is a typical problem with continuously recording water quality sensors.

The development of business rules for the real-time correction of data are defined for a specific parameter such as EC, at a specific geographical location. The rules are defined and then chained together with the simplest rule correcting the largest amount of data applied first to correct the data before the next rule is applied. The rule defined for one location may or may not apply to other parameters in other geographical locations.

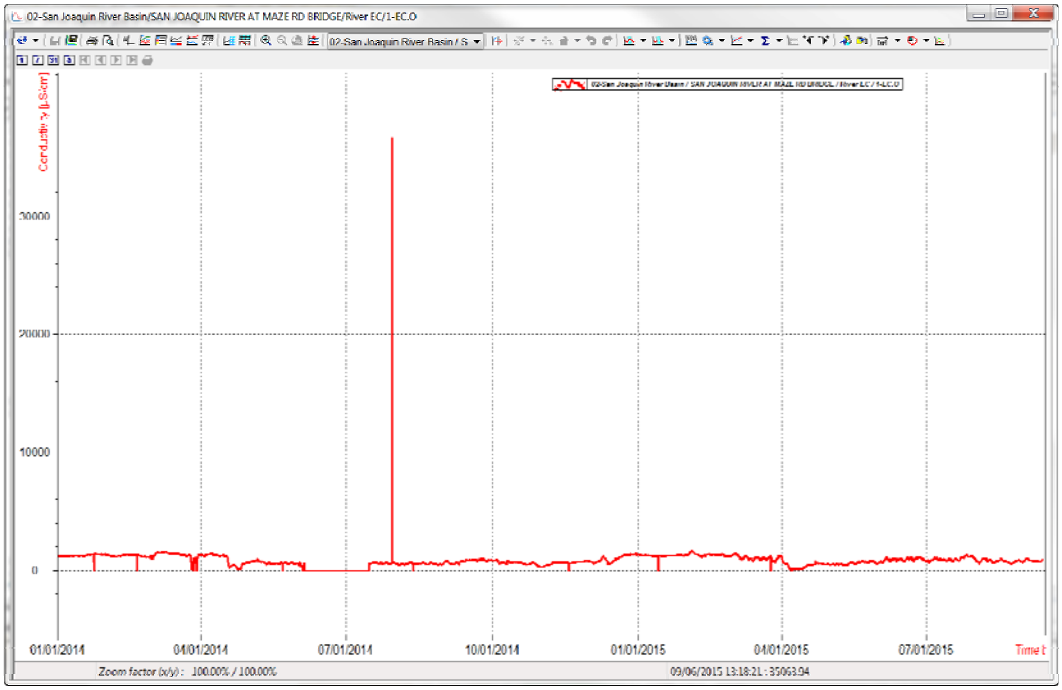

Figure 4 Values of Conductivity from the San Joaquin River at Maze Blvd

Figure 5 is an enlarged area of the spike from Figure 4. One can now see the detail in the noisy data that requires further refinement. Additional business rules will be required to further validate and correct the data.

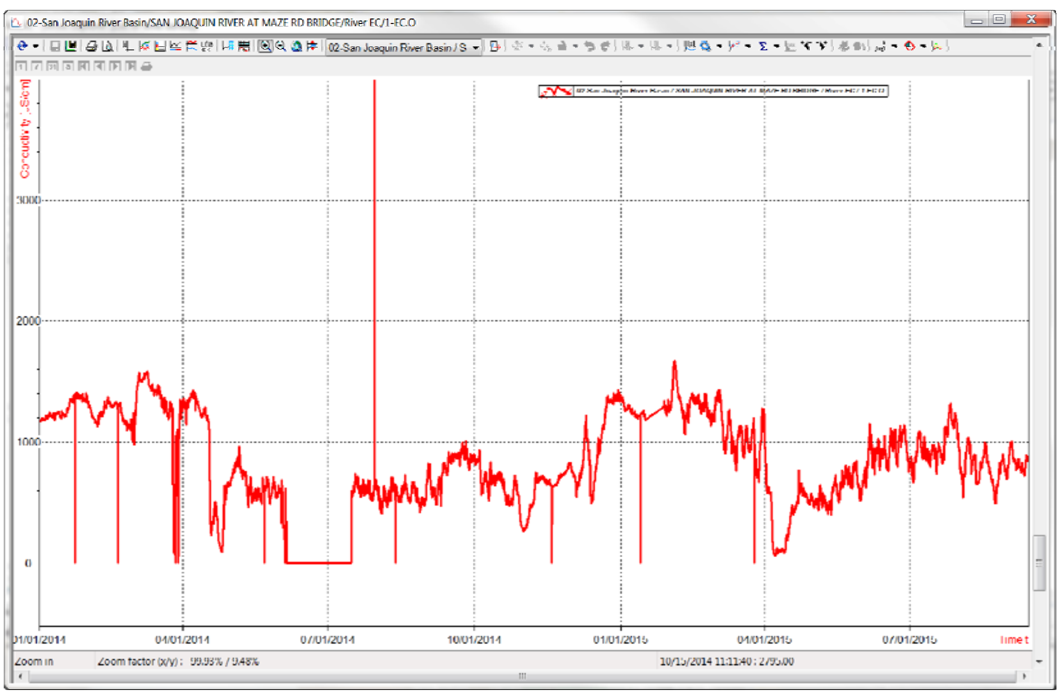

Figure 5. A zoomed-in portion of Figure 4 above

Figure 6 shows the final corrected data after all of the business rules have been applied. More information about this site and discussions with the staff responsible for maintaining the stations and sensors may lead to further refinement of the data. Additionally, downstream or upstream EC stations may yield information about the issues with the data at this location. If there are no influencing factors between the upstream or downstream monitoring stations a business rule can be defined to compare the data from these stations to further qualify the questionable data.

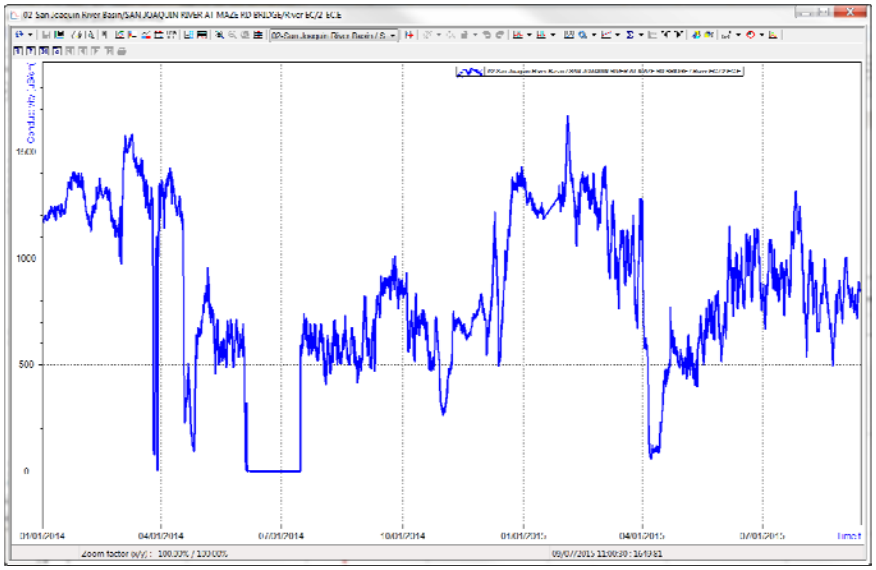

Figure 6. All business rules have been applied, data corrected

Figure 7 combines both the raw data (Red) and the validated data (Blue) for comparison.

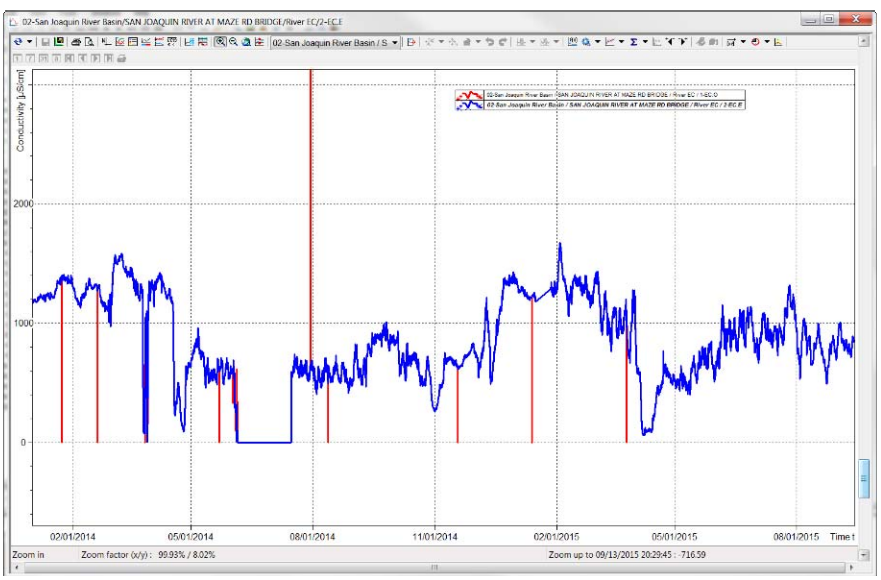

Figure 7. Comparison of the raw data (Red) and the corrected data (Blue)

The second example is a monitoring station located on the San Joaquin River near Patterson (SJP). This data is also plagued with noisy data, spikes that exceed 200,000 units as compared to an average value of 2,000 units and multiple values less than zero

The graph in Figure 8 shows the data with the business rules applied comparing the raw data (Red) to the corrected data (Blue).

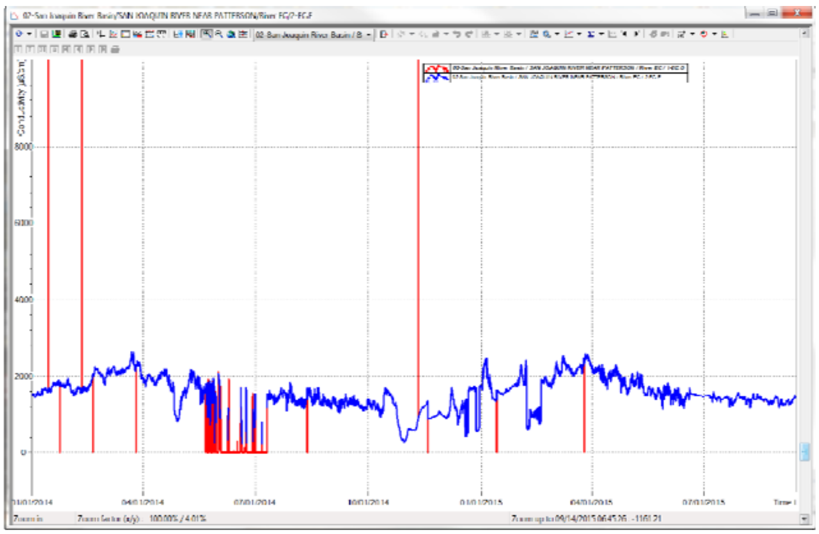

Figure 8. Comparison of the raw data and the corrected data

The last example is the compliance monitoring station on the San Joaquin River near Vernalis (VNS). This monitoring site is the target site for meeting the water quality objectives of the San Joaquin River. Table 1 is the water quality objective as agreed upon in the “The Water Quality Control Plan for the Sacramento River and San Joaquin River Basins For The Control of Salt and Boron Discharges into the Lower San Joaquin River, July 2004”, better known as the 2004 TMDL.

Table 1. Salinity and Boron Objectives for the lower San Joaquin River at Vernalis

SALINITY		
Reach	**Irrigation Season (Apr1-Aug31)**	**Non-Irrigation Season (Sep1 –Mar 31)**
Vernalis Only	700 µS/cm (30-day running avg.)	1000 µS/cm (30-day running avg.)
BORON		
Reach	**Irrigation Season (Mar 15-Sep15)**	**Non-Irrigation Season (Sep16-Mar14)**
Sack Dam to Merced River	2.0 mg/L (max.) 0.8 mg/L (monthly mean)	5.8 mg/L (max.) 2.0 mg/L (monthly mean)
Merced River to Vernalis	2.0 mg/L (max.) 0.8 mg/L (monthly mean)	2.6 mg/L (max.) 1.0 mg/L (monthly mean) 1.3 mg/L (monthly mean)*

Figure 9 displays both the raw and the validated data for comparison as collected from Vernalis monitoring station. Notice there is little error between the raw data and the corrected data during this period.

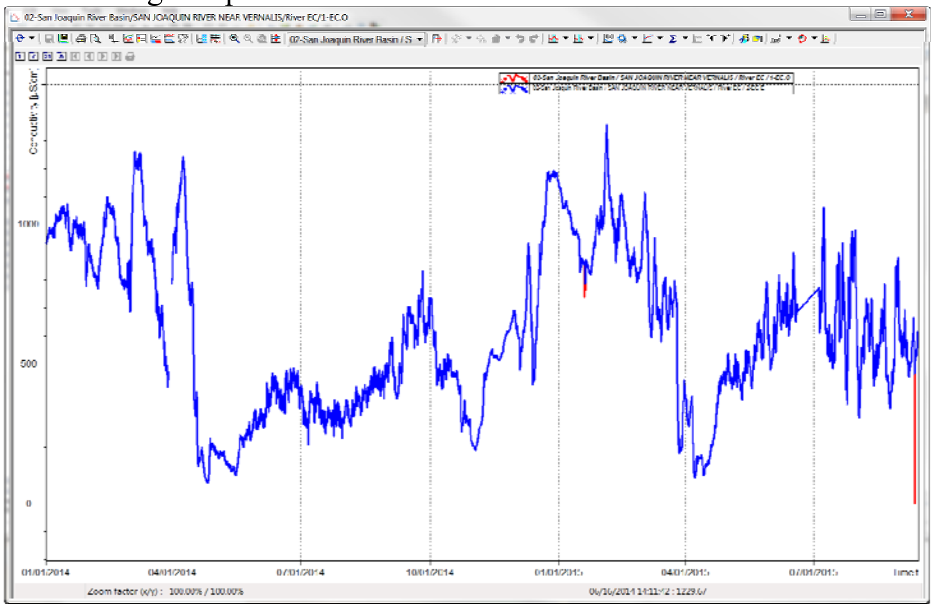

Figure 9. San Joaquin River near Vernalis comparison of the original data and the corrected data

Figure 10 displays the corrected data, the 30 day average and the seasonal limits as defined in Table 1 above. The 30 day running average allows reservoir operators the flexibility needed to achieve compliance while managing the water more efficiently allowing deliveries to junior water rights holders in the basin.

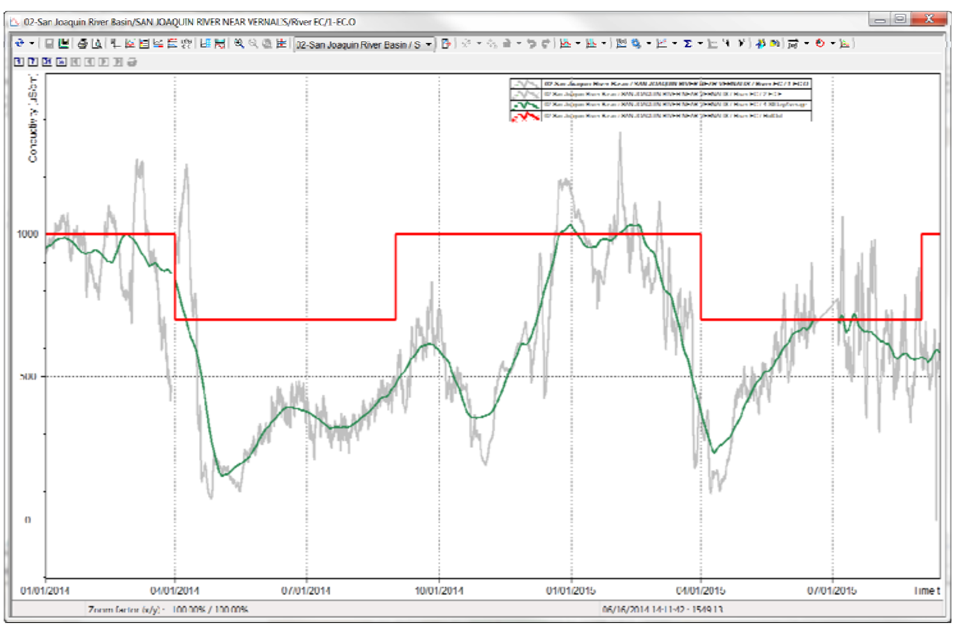

Figure 10. San Joaquin River near Vernalis 30 day running average and seasonal EC limits

As seen in the Figures, applying Business Rules to the data can provide a better quality of data for modeling and decision support. In Figure 10, the 30 day running average provides flexibility for reservoir operators to meet the seasonal salt compliance. Figure 10 also shows many days are out of compliance because of an insufficient monitoring and data sharing infrastructure throughout the basin. With the acceptance of the pilot project and basin wide expansion of the sensor network, real-time data management and data sharing as well as the use of WIMS such as WISKI, the Lower San Joaquin River water quality objectives, as defined in the RTMP, can be accomplished.

LONG TERM PLAN FOR CONTROLLING THE SALT AT THE WATER DISTRICT LEVEL

The pilot project was designed to look at the cost and efforts associated with a district level project to monitor and manage saline drainage releases to the San Joaquin River. This project will provide the basis for implementing similar programs at other key water districts on the west side that discharge either agricultural or wetland water to the San Joaquin River. It also applies to two municipal discharges that enter the San Joaquin River between Lander Avenue and Vernalis. The WIMS will allow district managers to time their releases when the river can support the additional salt load.

The next step after the districts have implemented a monitoring program will be to use the data sharing capabilities of the WIMS in the form of a web portal allowing all of the stakeholders to monitor the water quality of the San Joaquin basin in real time. Additionally, two key districts on the East side have already implemented KISTERS WIMS solutions and could play a major role in supplying dilutions flows when needed.

Finally, a completely automated system with sufficient data can be designed around a software based Optimization solution that would operate in real-time providing decision support information to all of the stake holders. With sufficient data an optimization solution will ingest all of the flow and EC values from all of the critical locations in the basin computing all of the releases necessary to reach the objectives at Vernalis. Once an optimization solution is operational it could be run daily or hourly, on an hourly basis a week in advance. In the case of an event, the solution can be manually run and have a solution in 5 to 10 minutes, dependent upon the size of the system being optimized. Additionally an alarm manager can be implemented to notify key districts of an impending problem.

CONCLUSIONS

Next steps in the program will require complete migration of the current GWD YSI-ECONET platform to a local data server running WISKI software and development of communication software to allow direct, automated data downloading to the local District-maintained database. This system will meet the low-cost objectives of the program and become an exemplar for adoption in other wetland management entities such as the California (State) Department of Fish and Wildlife, the Federal Fish and Wildlife service wetland managers and a large number of independent water districts that collectively belong to the San Joaquin Valley (Westside) Drainage Authority (SJVDA), which bears responsibility for the data monitoring networks being developed within the Basin. The SJVDA, teamed with an east-side San Joaquin Valley drainage authority will provide the institutional organizing impetus for successful implementation of this new concept in Basin-scale salinity management.

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ET-BASED IRRIGATION MANAGEMENT IN LEAF LETTUCE AND CABBAGE: RESULTS FROM 2015 TRIALS

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ABSTRACT

Estimation of crop evapotranspiration supports irrigation efficiency, which enhances water security and can mitigate nitrate leaching. Past research in California and elsewhere has revealed strong relationships between photosynthetically active vegetation fraction (Fc) and crop evapotranspiration (ETc). The U.C. Cooperative Extension developed and operates CropManage (CM), an online irrigation/nitrogen scheduling tool. CM accounts for the rapid growth and typically brief cycle of cool-season vegetables, where Fc and reference ET fraction (crop coefficient) can change daily during canopy development. The model automates calculation of crop water requirement based on reference ET data collected by California Dept. Water Resources. Empirical equations are used to estimate daily Fc time-series for a given crop type primarily as a function of planting date and expected harvest date. In the current study, replicated irrigation trials were performed on romaine lettuce and green cabbage at the USDA Agricultural Research Station in Salinas, CA. Lettuce was planted late April and harvested early July. Cabbage was planted mid-July and harvested early October. Following establishment by sprinkler irrigation, CM was used to guide drip irrigation treatments at 50%, 75%, 100%, and 150% of ETc replacement levels. Irrigation at 150% of ET did not affect marketable yields for carton lettuce, cored-for-region lettuce, or carton cabbage, relative to the 100% treatment, and all of the foregoing met or exceeded typical commercial yields. The 150% treatment produced highest yield in cabbage destined for the processed-product market. Irrigation at 50% and 75% of ET resulted in marked yield reduction in all cases. The experiments will be repeated in 2016.

INTRODUCTION

Irrigated agriculture consumes at least 80% of developed water supplies in the United States (Jury and Vaux, 2005). In California and throughout much of the western U.S.,

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municipal, agricultural, and environmental demands increasingly compete for limited surface-water supplies, while groundwater levels are declining. Constraints on supply and water quality in the state may worsen due to continued population growth, climate change, and declining water conveyance infrastructure. There is a need for low-cost adaptation strategies including use of irrigation scheduling technologies that incorporate information on weather conditions and crop growth stage. Support in this regard is provided by the California Irrigation Management and Information System (CIMIS), operated by the California Dept. Water Resources. CIMIS comprises a network of ~140 active stations that provide weather data and daily estimates of grass reference ET (ETo) in agricultural regions (Temesgen et al., 2005). Users may elect to access data from the nearest station or from Spatial CIMIS, which provides daily gridded ETo at 2 km resolution statewide (Hart et al., 2009). Effective use of ETo requires additional accounting for effects of crop type, development stage and site-specific factors. It is expected that the development and availability of convenient, user-friendly tools designed for a variety of commodities may serve to increase adoption of ET-based practices for on-farm irrigation scheduling.

One such tool is CropManage (CM), an on-line irrigation and nutrient management tool developed by U.C. Cooperative Extension (Cahn, 2012-2014) (Fig. 1). Irrigation recommendations are formulated by integration of soil, plant, irrigation system, and salinity information. Empirical equations are used to develop daily Fc time-series for a given crop type primarily as a function of planting date and expected harvest date (e.g., Fig. 2). CM uses Fc to generate daily Kc, which is then combined with CIMIS ETo to develop irrigation schedules tailored to daily crop water requirements of several crops grown on the Central Coast. The tool is accessible from a range of internet-connected devices, and is designed for convenience of use such that growers can determine irrigation schedules in timely fashion and maintain records of water applications for multiple fields and farms. The software is hosted on the Agriculture and Natural Resources communications server at the U.C. Davis Information Service Center. The goal of this project is to use CM guidance to examine yield response of two major Central Coast specialty crops, romaine lettuce and green cabbage, to various ET-based irrigation regimes.

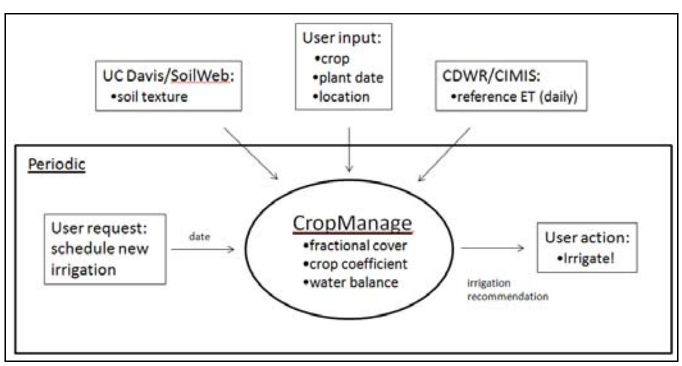

Figure 1. Overview of CropManage architecture.

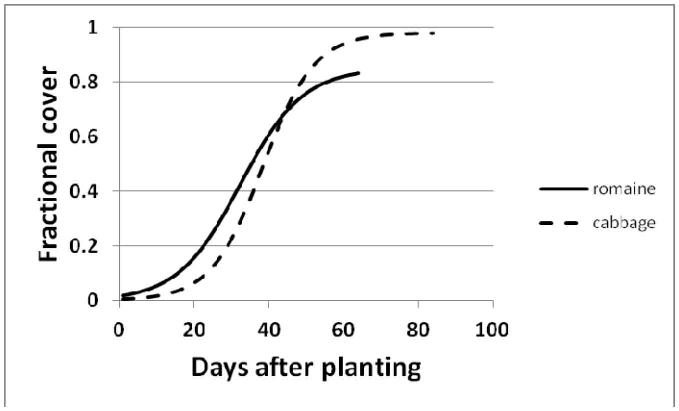

Figure 2. Crop development progression employed by CropManage for the crops of this study.

IRRIGATION TRIALS

Two irrigation trials were performed in 2015. Both experiments featured a complete randomized block design, with six reps of four treatments. Crops were planted on 40" beds with two seedlines per bed, on Chualar sandy-loam soils. The experiments were performed at the USDA Agricultural Field Station (Spence Ranch), near Salinas, CA. Four drip irrigation treatments (50ET, 75ET, 100ET, 150ET), nominally representing 50%, 75%, 100%, and 150% ET replacement for a typical romaine or cabbage crop, were applied in a 6-rep randomized block design. Main guidance for ET estimation was provided by the CropManage decision-support model. CM incorporated daily reference ET data collected and archived by the California Irrigation Management Information System (CIMIS) by measurement station #214 co-located at Spence Ranch. Applied water amounts for both sprinkler and drip were monitored by flow meters. Soil nitrogen status was monitored periodically by use of soil nitrate Quick-Test strips.

Leaf Lettuce (Romaine)

The field trial was conducted on romaine leaf lettuce (Sun Valley variety). The crop was planted from seed on 29-Apr-2015. Sprinkler-irrigation was used during the establishment phase, with thinning and conversion to surface drip 30 days after planting (DAP). Equal fertilizer amounts were applied throughout the field on DAP 29, 41, 48, 50, 51, 55, 58.

Field subsections were harvested on DAP 63 to estimate carton (fresh-product) yield. Resulting marketable yields were 11.8, 14.9, 22.6, and 21.4 t/ac for 50ET, 75ET, 100ET, and 150ET, respectively (Table 1), compared with a multi-county industry average of 15.5 t/ac reported for 2012 (CDFA, 2014). Corresponding applied water totals were 5.2", 6.2", 7.25", and 9.2" respectively, compared with typical applied totals of 12"-18" for Central Coast drip-irrigated lettuce (UC-ANR, 2011). Additional field portions were harvested for cored-for-region (CFR) bulk product by a commercial cooperator on DAP 64 (Table 2). Yields were 14.3 t/ac for both 100ET and 150ET, while 50ET and 75ET were deemed unready for harvest. The 100ET and 150ET yields both surpassed the 12.8 t/ac local industry average for fields harvested during the same the week per Fresh Express (pers. comm.). Corresponding applied water totals were 7.7" and 9.9". The 50ET and 75ET treatments were harvested for CFR by our commercial cooperator on DAP 71. Respective yields of 7.1 and 9.8 t/ac were well below local commercial yield average for the week of 14.6 t/ac. Corresponding applied water totals were 5.9" and 7.2". Rainfall of 0.63" was received in addition to all above applied water totals. Results to date suggest that irrigation at 100% ET was adequate to produce commercial romaine yields for both carton and CFR product, irrigation beyond 100% did not affect yield, and irrigation below 100% was associated with yield reduction.

Table 1. Carton romaine results. Means comparison shown by superscripts.

Treatment	Irrigation (in.)	Yield (tons/ac)	DAP
50ET	5.2	11.8[a]	63
75ET	6.2	14.9[b]	63
100ET	7.3	22.6[c]	63
150ET	9.2	21.4[c]	63

Table 2. CFR romaine results.

Treatment	Irrigation (in.)	Yield (t/ac)	DAP
50ET	5.9	7.1[a]	71
75ET	7.2	9.8[a]	71
100ET	7.7	14.3[b]	64
150ET	9.9	14.3[b]	64

Cabbage

The experiment was conducted on green cabbage (Supreme Advantage variety). The crop was planted from seed at 5" spacing on 15-July-2015. Sprinkler irrigation was used for crop establishment, with conversion to surface drip on DAP 28. Equal amounts of fertilizer were applied throughout the field on DAP 30, 41, 44, 45, 51, 62.

Field subsections were harvested for carton yield in two passes occurring 78 and 84 DAP. The carton harvest included heads weighing 2.5-3.3 lbs., in other words, excluding relatively small or large heads. Marketable yields were 2.8, 15.5, 21.3, and 23.5 t/ac, respectively, for the four treatments (Table 3). 100ET and 150ET yields were in-line with local industry average near 22 t/ac during 2013-14 (Monterey County Crop Report, 2014). Additional field subsections were harvested for cored-processed product yield (all heads >5" diameter) on DAP 86. Marketable yields were 6.7, 21.9, 30.9, and 35.4 t/ac respectively, for the four treatments (Table 4). While industry comparison data are scarce, two local fields harvested during the same week (possibly on more productive soils) yielded approximately 40 t/ac (Dole Fresh Vegetables, Inc., pers. comm.). Corresponding applied water totals for all harvest operations were 8.7", 10.9", 13.3", and 17.1", plus 0.38" rain (Table 4), compared to 12"-18" typically applied for cabbage via combination of sprinkler and drip (UC-ANR, 2008). Results to-date indicate that irrigation at 100% ET replacement was adequate to produce commercial yields for carton product, and that irrigation beyond 100% did not affect carton yield. Irrigation beyond 100% did serve to increase yield of cored-processed product, while limited data suggest that both treatments fell short of local industry average for this product type. Applied water below 100% ET greatly reduced yield of both products.

Table 3. Carton cabbage results.

Treatment	Irrigation (in.)	Yield (t/ac)	DAP
50ET	8.7	2.8[a]	78,84
75ET	10.9	15.5[b]	78,84
100ET	13.3	21.3[c]	78,84
150ET	17.1	23.5[c]	78,84

Table 4. Cored-processed cabbage results.

Treatment	Irrigation (in.)	Yield (t/ac)	DAP
50ET	8.7	6.7[a]	86
75ET	10.9	21.9[b]	86
100ET	13.3	30.9[c]	86
150ET	17.1	35.4[d]	86

CONCLUSION

Irrigation trials were performed on romaine lettuce and green cabbage during 2015. The CropManage decision-support tool was used in conjunction with CDWR/CIMIS grass-reference ETo data to guide irrigation scheduling at various ET replacement levels. Results from the first-year experiments suggest that irrigation at 100% replacement was adequate to produce commercially viable yields of carton romaine, carton cabbage and CFR romaine. Excepting cored-processed cabbage, irrigation above 100% did not affect yield, while yield penalties were associated with lower levels of water replacement (50%, 75%) in all cases. For romaine, applied water totals were well below the crop water requirement per UC-ANR (2011). The experiments will be repeated in 2016.

ACKNOWLEDGEMENTS

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INCREASING AGRICULTURAL WATER USE EFFICIENCY IN THE LOWER GUNNISON RIVER BASIN, COLORADO

David Kanzer[1]

ABSTRACT

Due to projected water supply and demand imbalances and environmental concerns in the Colorado River Basin, water managers in the Lower Gunnison River Basin have embarked upon a multi-year, multi-million dollar systematic and comprehensive effort to increase agricultural water use efficiency. This effort is focused upon upgrading aging agricultural water infrastructure (*e.g.,* installing integrated pipelines, controls and sprinklers) to reduce deep percolation and minimize non-productive water losses to reduce saline and seleniferous runoff while meeting root zone needs, increasing agricultural productivity and conserving water to increase resiliency.

In July of 2015, the Colorado River District (CRD), as the lead partner on behalf of a broad coalition of 30 partners, entered into a cooperative agreement with the Natural Resources Conservation Service (NRCS) under the Regional Conservation Partnership Program (RCPP), to "*Modernize Agricultural Water Management in the Lower Gunnison River Basin."* Known as the Lower Gunnison Project (LGP), this 5-year, cooperatively-funded (totaling approximately $50 million), series of projects will study, design and implement modernization and system optimization activities within the Lower Gunnison Basin on the western slope of Colorado. The LGP includes work in four federal US Bureau of Reclamation (USBR) irrigation areas that include the Bostwick Park, Paonia, Smith Fork and Uncompahgre Projects.

The LGP objectives are: 1) to increase agricultural water availability by minimizing system losses; 2) to enhance water quality by minimizing salt and selenium loading associated with seepage, deep percolation and runoff; 3) to address declining soil health issues, typically associated with water logging, salinization, and organic carbon content deficiencies; and 4) to benefit in-stream habitat quality, in selenium-affected, critical habitat for the benefit of threatened and endangered species. These project objectives not only address high priority natural resource concerns but they also help comply with federal Endangered Species Act and Clean Water Act regulations and stretch water supplies.

This paper outlines the historical context, compelling issues, and cooperative approaches designed into the LGP to meet multiple goals and objectives.

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INTRODUCTION

High priority natural resource concerns (degraded water quantity and quality as well as impaired aquatic habitat and poor soil health) have been identified by regulators and managers in the Lower Gunnison River Basin, which encompasses the Gunnison River and its tributaries below Morrow Point Dam, near Cimarron, Colorado to the confluence of the Colorado River near Grand Junction.

The Lower Gunnison River Basin area is characterized by significant agricultural activity served by aging irrigation infrastructure, with saline and selenium-rich geology and derived soils. The project area boasts diverse high quality agricultural production, including field and sweet corn, forage crops, such as alfalfa, grass hay, wheat, barley, and oats as well as some more limited fruits and vegetables. Such produce can include hops, beans, peppers, onions, broccoli, potatoes, squash, vegetable seed, melons, grapes, peaches, apples, pears, cherries, apricots. Livestock operations are common and include cow-calf operations, beef and dairy cattle, sheep, hogs, horses, chickens, and even domesticated elk and bison.

There are four primary irrigation ‘focus areas’ within the project boundary (shown in blue on Figure 1) that includes all or portions of the following tributary sub basins: North Fork Gunnison River, Smith Fork of the Gunnison River, the Cimarron River and the Uncompahgre River sub-basins with a drainage area of approximately 3,600 square miles and includes all or parts of four hydrological unit codes (8-digit HUCs 14020002, 14020004, 14020005 and14020006). Elevations in the project areas range from approximately 6,000 ft AMSL near Paonia to about 4,500 ft AMSL near Grand Junction.

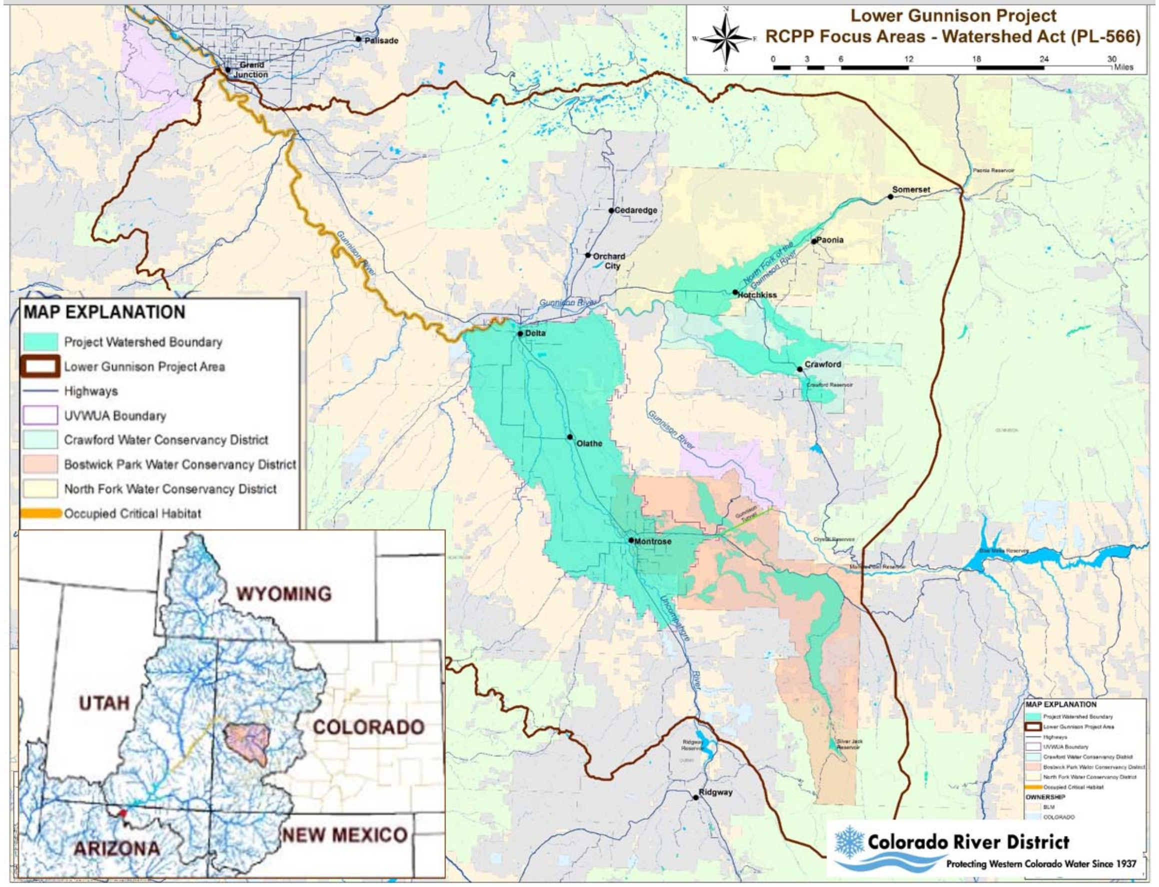

Figure 1. Map of the Lower Gunnison Project Area

Endangered fish species, including the Colorado pikeminnow and razorback sucker, occupy federally-designated critical habitat in the Lower Gunnison River downstream of the confluence of the Uncompahgre and Gunnison Rivers near Delta, Colorado. In addition, several 'species of special concern,' subject to a multi-state "range-wide conservation agreement and strategy agreement," also occupy the majority of the Lower Gunnison River Basin. These include the roundtail chub, as well as the flannelmouth sucker and the bluehead sucker.

Because the LGP is located in the headwaters of the drought-affected Colorado River Basin (CRB), this project will have positive, long-term benefits for downstream states and communities (approximately 40 million people in the US alone) that rely upon the CRB for domestic, municipal, industrial and agricultural water supplies and for associated environmental and recreational benefits.

To achieve the natural resource objectives and benefits, the LGP implements a locally coordinated comprehensive strategy of maximizing agricultural water use efficiency through: 1) system-wide optimization planning and design techniques for irrigation water conveyance, including the construction of carefully-monitored, automated, re-regulation structures; 2) modernization of aging irrigation water delivery infrastructure including the construction of enclosed canals and laterals and installation of Supervisory

Control and Data Acquisition (SCADA) systems; and 3) implementation of locally-adapted, on-farm high efficiency irrigation systems (e.g., sprinklers, drip) in conjunction with expanded implementation of soil health practices (e.g., minimum till, cover crops).

This approach is unique and is contrary to traditional "buy and dry" practices that transfer and remove critical water resources from agricultural lands to municipal uses in other areas of the CRB, and in adjacent basins within Colorado. This cooperative project promotes agricultural and community sustainability and makes water available to meet multiple human and environmental objectives by increasing water conservation by reducing water loss via seepage and deep percolation. Environmental benefits include reduced salt and selenium loading to the stream system and improved stream flows that provide improved habitat conditions for threatened and endangered aquatic species.

In addition to benefits, it is important to note that there can be adverse impacts associated with water use efficiency improvement projects. For example, as less irrigation water is applied, soil moisture can decrease and salinization can occur. The LGP utilizes monitoring and management techniques to guard against such adverse impacts to the root zone. Additionally, impacts can occur to irrigation-induced wetlands that receive less inflow as the result of decreased deep percolation. The LGP mitigates the loss of such wetlands and related habitats as a requirement under NEPA.

Previous to the LGP, there were related water use efficiency improvement activities that were occurring in the Lower Gunnison sub-basin (e.g., selenium reduction activities, salinity control program investments, NRCS-funded on-farm improvements), but until the LGP, these were limited, disparate efforts without a unifying 'grand design' and without leadership from producers. In response, the LGP partnership was formed that includes agricultural producers together with irrigation water providers and a host of other partners, including environmental interests, with the intent of addressing water and soil resource concerns in a holistic way.

As part of this process, a new ad-hoc group was formed to investigate how to best increase 'on-farm' agricultural water use efficiency while incorporating the local soil and water conditions of the Lower Gunnison Basin. Self-titled, "*No Chico Brush*," this separately funded of agricultural producers has embarked upon a campaign to perform research and educate growers about agricultural sustainability by carefully studying the pros and cons of increasing 'on-farm' agricultural water use efficiency in conjunction with different soil health techniques. Together with their research partners, Colorado State University (CSU), the *No Chico Brush* group is a valuable advocate for on-farm interests.

The LGP now integrates funding, design and implementation activities and brings together diverse skill sets to produce greater water efficiency gains and multiple environmental benefits. Significant technical support is being provided by USBR and NRCS engineering and environmental compliance staff, Colorado River District engineers and water resource specialists, USGS and CSU experts, as well as other non-governmental specialists; this results in a significant leveraging and multiplication of benefits.

Results from the LGP will be documented through an existing and expanded basinwide network of water quality and quantity monitoring stations augmented with new discrete samples that may include additional tailwater and soil quality analyses. Increases in water quantity and availability will be measured through an enhanced network of surface water monitoring gauges, on-farm water monitoring (i.e., delivery and tailwater measurements), moisture monitors and agricultural production metrics. Soil quality improvements will be documented through comparative analysis of on- and off farm soil conditions using GIS and orthophotogrammetric methods using NAIP imagery and laboratory soil sample analysis (*e.g.,* increased carbon content, microbiological health, and soil physics such as field capacity). Improvements to degraded habitat for sensitive, threatened and endangered aquatic species will be documented by comparison to long-term published flow and selenium concentration and load monitoring records at several key monitoring locations downstream of the project areas and in conjunction with the Colorado River Endangered Fish Recovery Program and Selenium Management Program partners

HISTORICAL CONTEXT, BASELINE, AND TRENDS

Since the mid-1990's increasing attention has been paid to the Lower Gunnison River Basin, where studies show that significant salinity loading persists and from whence an estimated 30% of the selenium loads to Lake Powell originate (Engberg, 1999). Locally-led efforts began in 1997 after the State of Colorado lowered the allowable concentrations of chronic dissolved selenium levels to 4.6 ppb to protect the aquatic habitat of the endangered fishes. This regulatory action put most of the Lower Gunnison mainstem and tributaries into exceedance and therefore in direct violation of the Clean Water Act. In response, a Selenium Task Force was established that, in turn, helped to create a Selenium Management Program in conjunction with the USBR, the State of Colorado and other stakeholders.

Significant studies and implementation projects have now clearly established the link between the reduction of deep percolation of irrigation water to decreasing salt and selenium loads (Moore, 2011 and Richards, R.J., and Moore, J.L., 2015). Additionally, other USGS cooperatively-funded studies show that water conservation efforts such as piping canals and laterals and installing sprinklers, primarily through federally-funded activities, have reduced concentrations in the Gunnison near the mouth and Colorado Rivers at the Colorado state line by approximately 30 and 40%, respectively. (Mayo, 2012). The declining trend for the Lower Gunnison River from this report is shown as Figure 2.

However, there is still significant work to be accomplished and the LGP is using newly-available funding to further many of the activities identified by the Selenium Management Program and by the Salinity Control Program planning documents. For example, the Selenium Science Plan (Paschke, et al., 2014) outlines a series of the recommended activities to better define the selenium loading characteristics and scientific investigations that are needed to better understand geochemistry, groundwater, and related fate and transport issues.

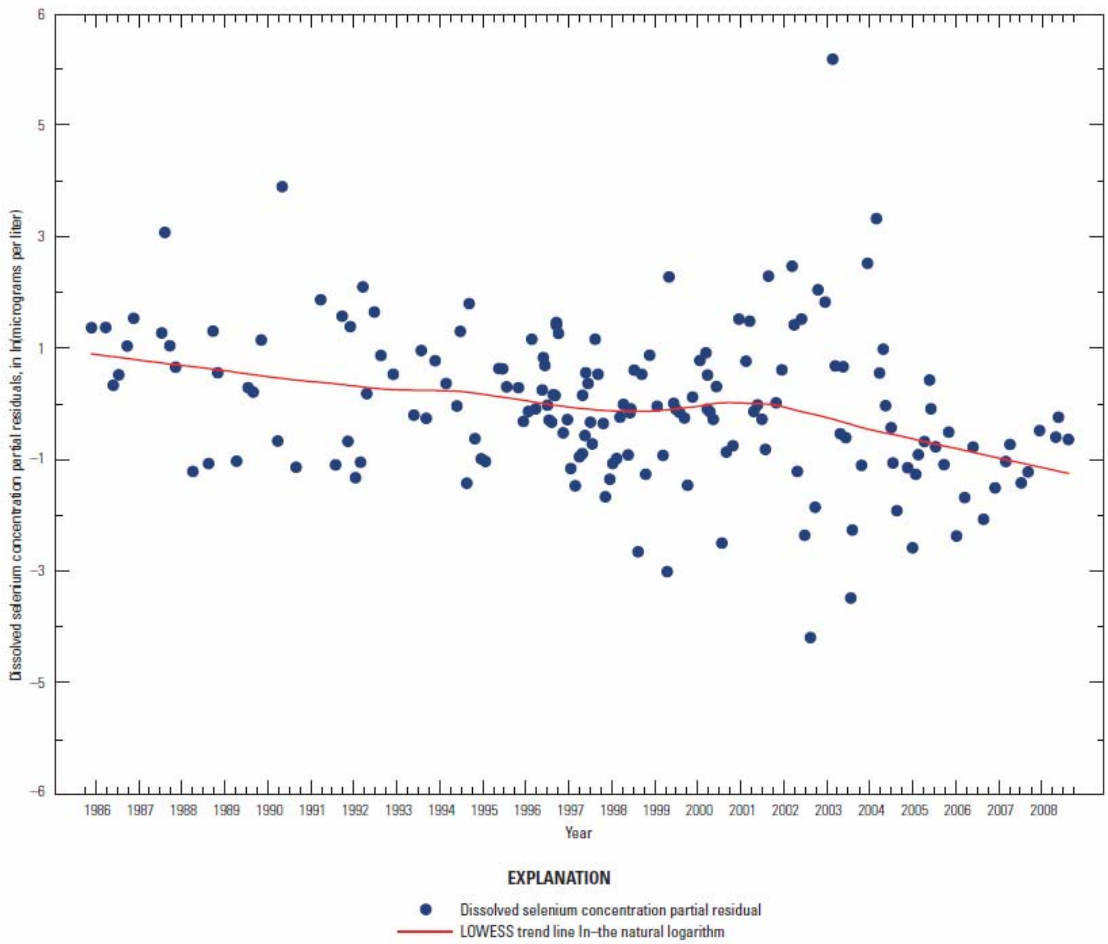

Figure 2. Declining trend of dissolved selenium in the Lower Gunnison River, Whitewater, near Grand Junction, Colorado, 1986-2008, estimated to be greater than 30% since 1986. Figure taken from USGS SIR 12-5088 (Mayo, 2012)

In addition, a USBR-funded report outlines a series of recommendations for additional salinity control efforts in the Lower Gunnison Basin (URS, 2013) and a ground-breaking system optimization study was completed by the Irrigation Training Research Center (ITRC, 2014) for the Uncompahgre Valley Water Users Association (UVWUA). These reports and additional on-going planning studies provide additional prioritization and implementation guidance to the Lower Gunnison Project partners. Such comprehensive and advanced planning is now characteristic of the LGP. As a partial result, the cost the effectiveness for salinity control has decreased or held steady for a number of years, as measured by cost per ton of salt controlled, amortized over the life of the implemented practice.

Based upon these and other data and planning documents, the LGP partnership has developed a prioritized list of water use efficiency improvement projects to meet the following implementation goals, consistent with the NRCS-RCPP funding criteria:

IMPLEMENTATION GOALS THROUGH 2020

1 - Action(s) to Increase Available Water Supplies (Insufficient Water Resource Concerns)

(1.1) Pipe approximately 60,000 feet of canals or laterals in the four focus areas from open, earthen ditches to enclosed pipe, pressurized where appropriate, along with construction of several re-regulation facilities, in order to minimize off-farm delivery system losses and to conserve up to 10,000 acre-feet of water per year

Funding Sources: NRCS PL-566, Reclamation FOA, other partner contributions*.

(1.2) Upgrade approximately 600 acres of irrigated farmland throughout the project area from flood irrigation to high efficiency irrigation systems (e.g. sprinkler or micro-irrigation) with corresponding irrigation water management plans, (including irrigation scheduling with real-time irrigation crop demand information) and education

Funding Sources: NRCS EQIP, Colorado State University, Colorado Water Conservation Board, other partner contributions*

(1.3) Incorporate 'smart' headgate diversion control structures and SCADA systems within the four focus areas to better manage irrigation water supplies, as appropriate and as budget allows

Funding Sources: NRCS PL-566; Reclamation FOA, other partner contributions*.

2 - Action(s) to Reduce Selenium and Salt Loading (Water-Quality Degradation Resource Concerns)

(2.1) Pipe almost 60,000 feet of canals or laterals in the four focus areas from open, earthen ditches to enclosed pipe, pressurized where appropriate, in order to reduce selenium loading by 400 lbs/year and salinity loading by 4,500 tons/year
Funding Sources: NRCS PL-566, Reclamation FOA, other partner contributions*.

(2.2) Upgrade at least 500 acres of irrigated farmland throughout the project area from flood irrigation to high efficiency irrigation systems (sprinkler or micro-irrigation) with corresponding irrigation water manage plans in order to eliminate groundwater deep percolation which contributes selenium and salt loading to the Gunnison and Colorado Rivers

Funding Sources: NRCS EQIP, Colorado State University, Colorado Water Conservation Board, other partner contributions*.

3 - Actions to Improve Soil Health (Reduce Soil Quality Degradation due to presence of salts)

(3.1) Implement soil health practices on approximately 600 acres

Funding Sources: NRCS EQIP, Shavano Conservation District, Uncompahgre Valley Soil Health Team, Colorado Water Conservation Board, other partner contributions*

4 - Actions to Assist in the Recovery of Endangered Species or Species of Special Concern

(4.1) Pipe / enclose approximately 60,000 feet of laterals or canals to reduce selenium load contributions by 400 lbs/year in order to improve aquatic habitat and to assist in the recovery of threatened and endangered species

Funding Sources: NRCS PL-566, Reclamation FOA, other partner contributions*.

(4.2) Pipe / enclose approximately 60,000 feet of laterals or canals to conserve water supplies by 10,000 acre-feet per year in order to in order to help achieve flow targets and to improve aquatic habitat and assist in the recovery of threatened and endangered species

Funding Sources: NRCS PL-566, Reclamation FOA, other partner contributions*.

* Other partner contributions include both cash and in-kind services provided by some of the 30 federal and non-federal partners. The list of partners in listed in Table 1 below.

Table 1. List of Partners in the Lower Gunnison Project

Partner	Type of Partner	Partner Role and Responsibilities
Colorado River District	Lead Partner	Provide overall project coordination
No Chico Brush	Technical, out reach, educarion	provide technical, policy and outreach support
Colorado Water Conservation Board (all grants / programs)	Technical and funding	provide funding for conservation practices
Colo Dept Public Health and Environment (NPS grants)	Funding, education, outreach	provide future funding for conservation practices, beneficiary
Colo Dept Agriculture / Colo State Conservation Board	Funding, education, outreach	provide funding for conservation practices
Colorado Water Institute	Monitoring, research, education	provide technical, applied research and outreach services, on-farm monitoring and evaluation
Colorado State University Extension	Monitoring, research, education	provide technical, applied research and outreach services, on-farm monitoring and evaluation
Irrometer	Technical and monitoring	provide technical services, limited in-kind support
Lehi Water, LLC	Technical and monitoring	provide technical services, limited in-kind support
PepsiCo.	Funding	Funding support
Nork Fork Water Conservancy District	Technical, project oversight,monitoring, education	construction monitoring, project administration
Crawford Water Conservancy District	Technical, project oversight,monitoring, education	construction monitoring, project administration
Bostwick Park Water Conservancy District	Technical, project oversight,monitoring, education	construction monitoring, project administration
Tri-county Water Conservancy District	Technical, monitoring, education and outreach	beneficiary
Uncompahgre Valley Water Users Association	Technical, project oversight,monitoring, education	construction monitoring, project administration
Crawford Clipper Ditch Company	Technical, monitoring, education and outreach	construction monitoring, project administration
Grand View Canal and Irrigation Company	Technical, project oversight,monitoring, education	beneficiary
Fire Mountain Canal Company	Technical, project oversight,monitoring, education	construction monitoring, project administration
Delta Conservation District	Technical, project oversight,monitoring, education	provide funding for conservation practices
Shavno Conservation District	Technical, project oversight,monitoring, education	provide funding for conservation practices
Delta County	Policy, education and outreach support	provide limited in-kind support
Montrose County	Policy, education and outreach support	provide limited in-kind support
The Nature Conservancy	Technical, project oversight,monitoring, education	provide funding for conservation practices
Trout Unlimited	Technical, project oversight,monitoring, education	provide funding for conservation practices
Walton Family Foundation	Funding and policy	provide funding and policy support for conservation practices
US Bureau of Reclamation (Salinity Program)	Technical and funding	provide funding for conservation practices
US Bureau of Reclamation (CRSP MOA)	Technical and funding	provide funding for conservation practices, off-farm monitoring and evaluation
US Geological Survey (Cooperative Program)	Technical	Conduct monitoring and evaluation
UC Endangered Fish Recovery Program	Technical	Conduct monitoring
Upper Gunnison River Water Conservancy District	Funding	provide funding for conservation practices
Western Slope Conservation Center	Monitoring and education	provide technical and outreach services

CONCLUSION

Although, much has been accomplished in the Lower Gunnison River Basin with respect to reducing salt and selenium loading through increasing agricultural water use efficiency, a series of large-scale projects are still needed: 1) to bring dissolved selenium levels into compliance with federal regulations, 2) to decrease salinity loading to minimize economic damages to downstream users, 3) to increase water quantity in amount and timing to help meet established flow targets to aid in the recovery of aquatic endangered species that occupy large reaches of the basin in federally designated critical habitat; 4) to address degraded soil health conditions and 5) to increase agricultural productivity, sustainability and profitability

The LGP is beginning to address these significant issues in a new comprehensive fashion using a large cooperative program that features over $50 million of cooperative investments. A large scale monitoring program is in place to evaluate these efforts and although it is too early to definitively claim success, downward trends have been quantified that indicate that the LGP will successfully expand previous efforts and water quality and quantity goals are attainable.

ACKNOWLEDGEMENTS

The author would like to sincerely thank and acknowledge many individuals and agencies involved in the Lower Gunnison Project. Without their tireless efforts, this project would still be a concept. This includes the Selenium Task Force (Sonja Chavez), the Selenium Management Program, the U.S. Bureau of Reclamation (Kib Jacobson), the US Geological Survey (Ken Leib), US Natural Resource Conservation Service (Clint Evans) US Fish and Wildlife Service (Barb Osmundson), Colorado Water Conservation Board (Steve Miller), Colorado State University (Dr. Perry Cabot), No Chico Brush (Tom Kay and others), the Nature Conservancy (Aaron Derwingson), Trout Unlimited (Cary Denison), and countless other public servants, landowners and interested citizens.

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COMMON MISTAKES IN SMALL DAM MAINTENANCE AND INSPECTION

Owen Kubit, PE, CFM[1]

ABSTRACT

Small dams require proper inspections and frequent maintenance to ensure a long-life. Experience is drawn from working with over twenty public agencies, private individuals and community organizations in the United States and overseas that own and maintain small dams. Several common mistakes were observed including lack of organizational structure and assigned responsibilities, lack of training, lack of knowledge on when to consult a professional engineer, ignoring impacts of wildlife on dams, over-reliance on anecdotal hydrologic information, spillway clogging, and inadequate valve exercising. Recommendations are provided for developing long-term maintenance and inspection plans to address these issues.

INTRODUCTION

Dam inspection and maintenance are important to prevent dam failures, extend the useful life of a dam, prevent interruption of project benefits, and reduce or delay the need for expensive rehabilitation. This paper provides guidance on dam inspection and maintenance primarily from lessons learned while inspecting numerous dams, including fifteen dam failures. The author has seen numerous trends in poor dam inspection and maintenance, which are discussed below. The recommendations focus on small and medium sized earthen dams owned by local public agencies, farmers, ranchers and irrigation associations.

MAINTENANCE VERSUS INSPECTION

Dam maintenance and inspection are mutually important and each should receive equal attention. Inspection is important to identify maintenance needs, however, if the maintenance issues are not addressed the inspections serve little purpose. Inspections are usually performed on a regular basis due to regulatory requirements for dam inspections. However, the author has seen numerous cases of maintenance recommendations from inspection reports being ignored year after year.

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Figure 1. Maintenance and Inspection Should Receive Equal Attention

Maintaining and inspecting dams requires some level of skill and experience. Problems often arise with a change in staff when the maintenance and inspection responsibilities are not adequately transferred. In some cases the inspection and maintenance efforts are reduced, in other cases they are ignored altogether.

DAM INSPECTION

Most dams should be inspected annually. Some exceptions include low hazard dams in remote areas that can be inspected every two to five years. Prior to performing an inspection the engineer should become familiar with the dam history, especially past problems and previous inspection reports. Some issues, such as seepage and erosion, occur at all dams, so the change from year to year is the most important.

Dam inspections should be performed by a qualified engineer with the dam owner or representative present. The benefits of being able to discuss the findings of the inspection with the owner are obvious. The dam owner can also share information on normal operations, unusual events since the last inspection, maintenance efforts, and other important information.

Caution should be taken when using anecdotal hydrologic information, such as high water marks, verbal descriptions of flooding, and informal measurements. While this data can still be useful it is often not accurate due to fading memories and improper measurement techniques. Though no longer common in the United States, some dams have been designed using anecdotal hydrology, resulting in inconsistent designs and undersized spillways.

DAM FAILURES

A primary reason to inspect and maintain dams is to prevent dam failures. Jia et al. (2007) collected data on 593 earth dam failures in over fifty countries, including the United States. They concluded that dam failures usually occur within five years of construction. Inadequate spillway capacity was identified as the largest problem and accounted for 36% of failures. Erosion and piping failures caused by poor quality construction were the cause of 43% of the failures.

Figure 2. Breach in Earth Dam, Ghana, West Africa

The National Performance of Dams Program (http://npdp.stanford.edu/) collected data on the causes of dam failures in the United State between 1975 and 2001. The results are shown in Figure 2.

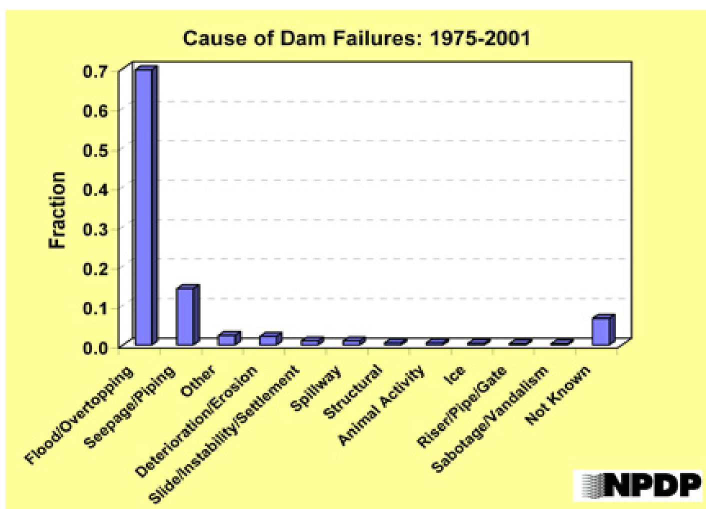

Figure 3. Dam Failures in United States from 1975-2001
Source: National Performance of Dams Program (2013)

This graph also shows that overtopping is the primary cause and seepage/piping is the second most common cause of failure, which is consistent with Jia et al. Clearly, important components of inspection/maintenance programs include the spillway and potential causes of erosion and piping.

SPILLWAYS MAINTENANCE

Spillways can become clogged with vegetation, debris, or rockfall, which reduce their capacity. The spillway channel should be cleared at least annually. Problems often arise on spillways that are only designed to spill in large storm events. Since they are rarely used maintenance efforts are sometimes ignored or forgotten. When a large storm arrives they may be clogged and have substantially reduced capacity.

Spillway maintenance should always include input from a dam engineer or other experienced professional. In some cases (especially with small private dams) the spillways are adversely modified. In one case, a spillway entrance was filled in with soil to increase total storage capacity, essentially removing all spillway capacity. In another case, a community removed a spillway beam to lower the spillway crest and increase spillway capacity. Without the beam the spillway eroded to the base of the dam, which essentially resulted in a fully breached dam.

TREES

Trees simply do not belong on earth dams. While the number of dam failures attributed to trees is small, they still present a risk. Root systems can create potential paths for a piping failure, and can also invade drain blankets and clog collector pipes. Trees are best removed when they are small since the entire root system must also be removed. If the root system is left in an embankment then the roots will rot and create a larger seepage path for piping failures. The author has seen some large trees left on embankments due to the difficulty, and risk, in removing the entire root system. The author has also seen a homeowners association plant trees on an earthen dam for aesthetics and to provide shade; these later had to be removed. In another case a tree blew over on a dam during a windstorm. The roots were pulled out of the ground creating a low spot and subsequently reducing the dam freeboard.

SEEPAGE

All dams leak so it’s important to note how much a dam leaks, changes in the leakage, and whether the water is turbid, which may indicate piping. Seepage from designed seepage systems (see Figure 4 below) is not necessarily alarming since they are designed to capture water.

Figure 4. Rehabilitation of Seepage System in Earthen Dam in Santa Clara County, CA

In one case, seepage was occurring in an earthen dam and created a small stream leading away from the dam. The maintenance personnel were not aware it was a serious issue and did not report it for several weeks. The area was excavated and recompacted with suitable backfill material.

VALVE EXERCISING

Valves should be exercised at least annually (and preferably semi-annually) to ensure they remain operational and do not build up rust or other deposits. Regularly exercising valves will also help to extend their life expectancy. The author has observed many cases where important valves, such as outlet works, were stuck and inoperable. The dam operators were aware of this situation but allowed the problem to persist for many years. In another situation a dam owner did not operate his valves because he could not find them. If valves are stuck the problem will not go away, and the problem should be rectified as soon as feasible. If outlet works cannot be opened in an emergency situation a dam may overtop and fail. When exercising valves they should be fully opened and fully closed; this can be documented with the total number of turns required.

A potentially dangerous situation occurred at one dam where the upstream valve was stuck open, and the downstream valve was left closed to prevent the reservoir from draining. This created a pressurized pipeline within an earthen embankment which persisted for several years. Leakage in the pipe could have saturated the dam and presented a significant safety hazard.

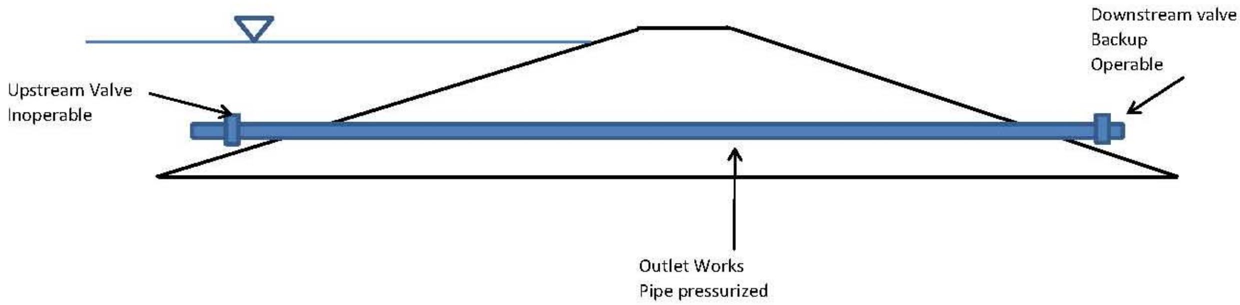

Figure 5. Dangerous Sitution of Pressurized Pipeline in Earthen Dam

EMERGENCY MATERIALS

Dam owners should pre-arrange emergency supply contracts or stockpile emergency materials such as rock, sand, sand bags, emergency bulkheads, or other operating equipment or supplies. The stockpiles are needed in case materials are not available on short notice, or during non-business hours. Materials can also potentially be available from other agencies (i.e. neighboring irrigation district) in the area, although during flood conditions the other agency may also need their materials and equipment. Stockpiles of emergency materials should be reviewed periodically.

BURROWING ANIMALS

In the United States, burrowing rodents and alligators pose problems at earth dams. Alligator burrows are well documented from observations at alligator farms. Borrowing animals such as squirrels and gophers are problems at many earth dams. Their burrows are narrow but can be deep and extend through a dam, creating a pathway for water and cause a piping failure.

Burrowing animals can be controlled by riprap, fencing placed flat on the dam surface, backfilling burrows, hunting, baiting and relocation. Burrows should be refilled with compacted, moisture-conditioned fill material. It is important to backfill the holes as this discourages reinfestation and any new activity is easy to detect. Riprap should include large angular rocks that interlock to improve stability and reduce movement. Rounded boulders or flat foliated boulders should not be used. An innovative way to control burrowing rodents is to place raptor perches near dams. This will attract raptors who will eat rodents and help control their population.

Figure 6. Raptor Perches for Rodent Control

On the Kings River Levees in Central California, the United State Army Corps of Engineers surveyed the location of every rodent hole on 150 miles of levees (hundreds were identified). While this may seem excessive, it does illustrate the importance some government agencies place on controlling rodent burrows.

In other countries crocodiles present a significant risk to dam failures. Crocodiles can dig deep burrows in dam embankments for shelter and to lay eggs. These burrows are typically deeper than alligator burrows and can extend through an entire embankment. The author assisted a community with removing a crocodile from an irrigation reservoir in West Africa.

Figure 7. Crocodile Removal at Irrigation Dam in West Africa

DAM INSPECTION AND MAINTENANCE GUIDELINES

Several valuable references are available on dam inspection and maintenance. In 1987, the State of New York prepared "*An Owners Guidance Manual for the Inspection and Maintenance of Dams in New York State*". The author has found this document one of the most comprehensive and useful refereces on the topic. It is a guidance document, as opposed to a regulatory document, and the information is useful and relevant for dams throughout the United States. Many states also have their own guidelines published by their State Dam Safety Office.

CONCLUSION

The author has seen numerous trends in poor dam inspection and maintenance, especially improper dam operation or dam modifications made without consulting an engineer. Dam maintenance and inspection are mutually important and each should receive equal attention. Dam inspections should be performed with the dam owner or representative present so information can be shared. Caution should be taken when using anecdotal hydrologic information since the accuracy of the information is questionable. Studies show that inadequate spillway capacity and piping/erosion are the leading causes of dam failures, and these issues should be priorities in inspection and maintenance programs. Spillways should be kept clear of vegetation and debris to ensure their capacity is maintained. Routine valve exercising is important to ensure the valves can be operated in emergencies. Burrowing animals are a threat to most earth dams and require regular control using baiting, traps, or raptor purchases. Existing burrows need to be backfilled and compacted properly.

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CALIFORNIA'S SUSTAINABLE GROUNDWATER MANAGEMENT ACT: DEVELOPING SUPPLIES FOR GROUNDWATER REPLENISHMENT

Steve Macaulay P.E.[1]

ABSTRACT

This paper addresses the need and methodologies for developing additional water supplies to replenish California groundwater aquifers, many of which had been greatly depleted by extended drought conditions from 2012 through 2015, and many that have experienced overdraft over the past 30 or more years.

The need for developing additional groundwater replenishment supplies is driven by California's 2014 Sustainable Groundwater Management Act (SGMA). SGMA was signed by Governor Jerry Brown in late 2014, and defines sustainable groundwater management as the management and use of groundwater without causing specific "undesirable results". During the first year of implementation it became clear to water management professionals that meeting the SGMA requirements of sustainable groundwater management over the next 20+ years would require a combination of demand reduction and groundwater aquifer augmentation.

SGMA puts implementation responsibility directly on local agencies, with groundwater sustainability plans (GSPs) developed for more than 120 groundwater basins throughout the state. DWR has specific requirements to develop regulations and additional technical information to guide local agencies. One requirement is to develop a report by December 2016 on the potential for new supplies to replenish local groundwater basins. Complimentary to an expected policy-level presentation by DWR at the conference, this paper will provide important details about the direction of the report and how it might be used by local agencies as they prepare their GSPs.

The author is a consultant to DWR for SGMA implementation. He presented several papers on this subject at the June 2015 USCID conference in Reno, and is active in discussions on this topic among experts in the California water community.

BACKGROUND: CALIFORNIA WATER LAW

California surface water rights were initially riparian and self-enforced. Towards the end of the 19th century appropriative water rights to regulate surface water diversions and use were added to the institutional framework, and such rights have been administered by state government since 1914. As part of the 1914 Water Commission Act, there was consideration of regulating groundwater in earlier versions of the law. However, the final version that was signed did not address regulation of groundwater. As a consequence, groundwater use in California has been largely unregulated since 1914 with the exception

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of legal adjudications, where the courts administer groundwater use. Groundwater adjudications have largely been limited to urban areas in southern California.

The water balance for groundwater in storage is simple: when pumping exceeds recharge, aquifer storage is depleted. As a result of California's unregulated use, and as a consequence of the expansion of irrigated agriculture throughout the state in excess of development of surface water supplies, long-term groundwater overdraft has been estimated at up to 1.5 million acre-feet per year[2]. During the current drought that began in 2012, withdrawals have likely greatly exceeded this annual average overdraft estimate due to the severe reduction in available surface water supplies. This has further aggravated a number of longstanding problems associated with overdraft: (1) continued and in some cases accelerated land subsidence, (2) the need to drill deeper and deeper wells to maintain agricultural production, and (3) the drying up of a number of domestic and small urban water supply wells in some agricultural areas.

In 2014 -- 100 years after California began regulating surface water supplies -- the California Legislature developed, and Governor Jerry Brown signed the 2014 Sustainable Groundwater Management Act (SGMA). SGMA requires 127 medium and high priority groundwater basins in the state (representing more than 90 percent of California's population and irrigated farmland) to achieve sustainable conditions by 2040, with intermediate targets and requirements.

BASIC PROVISIONS OF SGMA

Background

In 2010, California irrigated an estimated 9 million acres of cropland using roughly 25 million acre-feet of applied water. On average, groundwater has supplied at least 30 percent of this total, and a much higher percentage when surface water supplies are reduced. Groundwater is also used extensively to meet municipal and industrial demands. In 2010 total California water use was about 43 million acre-feet, of which more than 16 million acre-feet was from groundwater.

California has encouraged development of groundwater management plans for more than a decade, with financial incentives related to access to state water bond funds. However, such plans largely have lacked the proper mix of legal and institutional authorities needed to adequately manage groundwater in a comprehensive way. So while there are a number of groundwater management success stories in various subbasins throughout the state, on the whole groundwater management at the end of 2014 was at a crossroads – particularly given the increased reliance on groundwater during the continuing prolonged drought.

[2] Thomas Harter and Jay R. Lund. U.C. Davis Center for Watershed Sciences. California Water Blog, California's Groundwater Problems and Prospects. January 30, 2013. https://californiawaterblog.com/2013/01/30/californias-groundwater-problems-and-prospects/ .

Background and details related to provisions of SGMA are contained in the USCID paper prepared by Macaulay and Joseph[3], presented at the June 2015 USCID conference in Reno and published in the conference proceedings. In general, SGMA defines ***sustainable groundwater management*** as the "management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results" {California Water Code § 10721(u)}. "***Undesirable results***" are defined in the legislation as any of the following effects caused by groundwater conditions occurring throughout the basin {California Water Code § 10721(w) (1-6)}:

- Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply
- Significant and unreasonable reduction of groundwater storage
- Significant and unreasonable seawater intrusion
- Significant and unreasonable degraded water quality
- Significant and unreasonable land subsidence
- Surface water depletions that have significant and unreasonable adverse impacts on beneficial uses of the surface water.

SGMA puts DWR in a supportive role: (1) developing regulations that guide the formation of groundwater sustainability agencies (GSAs) within defined groundwater basin boundaries; and (2) developing regulations setting forth the components of groundwater sustainability plans (GSPs). SGMA puts the authority at the local level to create GSAs and prepare GSPs. More on overall SGMA progress, as well as DWR's progress in developing regulations, will be presented by DWR on the first day of the San Diego conference. In general, groundwater basins will need to achieve sustainable water management by the year 2040.

GSAs are currently in the process of being formed, based on meetings and dialogue within many of the 127 groundwater basins subject to SGMA. The law requires that GSAs be formed by June 2017, with initial GSPs submitted to DWR by January 2020 or January 2022 (the earlier deadline is for those groundwater basins subject to critical conditions of overdraft, with such basins recently identified by DWR[4]).

Groundwater Sustainability Plans

On February 18, 2016 DWR released draft regulations setting forth proposed requirements for the components of GSPs[5]. The draft regulations say in part, "Plans must identify when and where groundwater conditions cause problems, such as seawater intrusion; the specific projects and management actions that local agencies will

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[3] Steve Macaulay and Trevor Joseph. California's Sustainable Groundwater Management Act: Background and Implementation. Presented at the USCID conference, Sustainable Basin Water Management — Challenges of Supply and Demand Management at the Basin Scale
Reno, Nevada — June 2-5, 2015. Paper published in conference proceedings.

[4] Department of Water Resources. Final List of Critically Overdrafted Basins. January 2016. http://www.water.ca.gov/groundwater/sgm/cod.cfm .

[5] Department of Water Resources. Sustainable Groundwater Management Act, Draft Emergency Regulations for Groundwater Sustainability Plans and Alternatives. February 18, 2016. http://wwwdwr.water.ca.gov/groundwater/sgm/pdfs/DRAFT_GSP_Emergency_Regulations_021816.pdf .

implement to prevent the problems; and milestones to track plan progress." It is clear that in order for GSPs to succeed in achieving "sustainable groundwater management" by 2040, a combination of actions would be needed. Based on dialogue within the broad water community including public interest groups, it has become clear that such actions would include consideration of the following, depending on the severity and magnitude of the sustainability "deficit" within each basin:

- Some control over groundwater withdrawals
- Additional actions to put more water into groundwater storage

GSPs are assumed to include a list of specific projects within these two general action categories. Initial GSPs are not likely to be project-specific since they are due in 2020/2022. However, GSPs are required to be updated every five years. Putting more water into groundwater storage will require getting a better handle on currently unused or under-utilized water supplies, which – during the current prolonged drought -- seems problematic. But the drought will end, and GSAs will need to consider a broad range of potential water sources to help replenish groundwater storage. This is where DWR's required report on "Water Available for Replenishment" comes in.

<u>"Water Available for Replenishment" Report</u>

Within SGMA, here is the only text setting forth the requirement that DWR prepare this report [California Water Code Section 10729(c)]:

> *The department shall prepare and publish a report by December 31, 2016, on its Internet Web site that presents the department's best estimate, based on available information, of water available for replenishment of groundwater in the state.*

With no available legislative history to explain the presence of this requirement, discussions were held in mid-2015 with participants in the negotiations leading to development of all SGMA language. As consultant to DWR, author was tasked to get initial input from various external groups and provide that input to DWR prior to any work on the report. Such input was developed through a number of meetings in July and August 2015, with subsequent briefings by DWR to its various SGMA advisory groups including its Practitioners Advisory Panel (PAP) made up of public agency and consultant practitioners in groundwater programs throughout California. DWR staff prepared an annotated outline of the Water Available for Replenishment (WAFR) report and received additional input from its advisory groups throughout the fall of 2015. In January 2016 DWR staff released a white paper providing more details on contents of the report, reflecting input it had received on the earlier annotated outline.

INITIAL INPUT FROM WATER USER COMMUNITY AND ADVISORY GROUPS

As anticipated, DWR received a great deal of input and ideas from its SGMA advisory groups and the overall water community. Some of this input was contradictory, reflecting various interpretations of what the California Legislature may have intended in the one-sentence requirement in SGMA. Some input suggested that DWR limit its evaluation to under-utilized wet year water supplies that could be delivered to much of California through its large developed water projects, with a focus on the California State Water Project and the federal Central Valley Project. Other input suggested that DWR focus its analysis on only those potential additional water supplies that might be available at the basin level from water resources already within the basin. Some of this was suggested to include stormwater flows that currently flow out of the basin. This was of particular concern to those groundwater basins adjacent to the Pacific coast, where stormwater flows discharge to the ocean.

Some differences were also noted in comments. There were differences as to whether or not additional use of recycled water should be included in the report (particularly additional treatment of urban wastewater supplies for direct or in lieu groundwater recharge). DWR has received comments regarding how water conservation should be handled, with some comments suggesting that this is a demand reduction measure that would not necessarily improve groundwater storage (and in fact might result in reductions due to reduced deep percolation of applied irrigation water). Additional comments and suggestions included brackish water desalination for inland basins as well as ocean desalting along the coast. There were also suggestions that DWR rely heavily on local water resources studies that have been developed as part of integrated regional water management plans, an effort supported by state bond funds and policy over the past 20 years.

DWR APPROACH

White Paper

In January 2016 DWR released a white paper for review[6], reflected its more thorough thinking of what the WAFR report could address in the relatively short timeframe for preparing the report. The approach to the report will be to rely as much as possible on existing information, including published studies at the local and state levels. There is some time and some budget to collect and analyze data, but the Legislature provided only limited time and guidance for the report. DWR is mindful that the purpose of the WAFR report is to help local agencies as they prepare their GSPs and over time develop projects to augment groundwater supplies.

Table 1 is a summary of current thinking about how the WAFR report will be organized and what it will contain.

[6] Department of Water Resources. Water Available for Replenishment White Paper. January 20, 2016 Working Draft.

Table 1. Water Available for Replenishment Report, General Outline

Chapter	Contents
Introduction, Purpose, Summary	Definitions, terminology, overall report summary
Description, "Water Available for Replenishment of Groundwater"	Describe methodology and approach, tie to SGMA requirements for what constitutes sustainable groundwater management in the context of locally-developed GSPs, identify potential sources of supply and how they could fit into basin water balance, etc.
Challenges, uncertainties	Current and future challenges, data availability, water quality, infrastructure, institutional/regulatory constraints, environmental and financial challenges, climate change, population and land use changes, etc.
Outreach, outcomes	Legislative timeline, outreach, outcomes
Results, next steps	Findings, identify how information could be used by GSAs in preparing GSPs and subsequently develop specific projects, "cookbook" on how to refine analyses as project-specific information is developed, etc.

Here is a list of potential sources of water identified to date, recognizing that there are conflicting comments on the utility of some of these sources for the purposes of the WAFR report:

- Surface Water
- Desalination
- Conservation
- Recycling
- Water Transfers

Technical Approach

DWR plans to develop regional estimates of supplemental water supplies that could be available for replenishment, subject to development of local projects by GSAs. The regional estimates will be developed by hydrologic regions, similar to work done in the 2015 Update to the California Water Plan. Estimates will also be completed for each potential water source. There are only ten hydrologic basins, essentially representing major surface water basins. Information may or may not be broken down by groundwater basins, so GSAs will need to develop more specific information in support of local projects that could replenish groundwater.

The WAFR report will also include suggested methodology in the form of roadmaps or guidelines for both direct and in lieu recharge, setting forth how project-specific estimates could be developed at the local level once a proposed project is suggested for inclusion in a GSP. Different roadmaps/guidelines will be developed for each potential source of water, and there will be project-specific roadmaps/guidelines for both direct and in lieu recharge. There is some consideration for including case studies – real or theoretical – to show how the roadmaps/guidelines could be applied.

DWR will rely heavily on information already available from a wide range of state and local sources, and will consult with subject matter experts on a regular basis (both those within state government and others outside of government).

The author's opinion is that one area of potential concern is stream environmental resource being tied in some basins to groundwater conditions. In some stream systems this is a potential conflict between maintaining existing stream flow conditions and investing in groundwater recharge to help reduce future dry-year stream flow depletions. This may be an issue in some basins, and will presumably be addressed in GSPs.

Time Line

Figure 1 is a general time line for preparing the WAFR report, taken from a PowerPoint presentation[7] made by DWR staff to its advisory groups in January and February 2016.

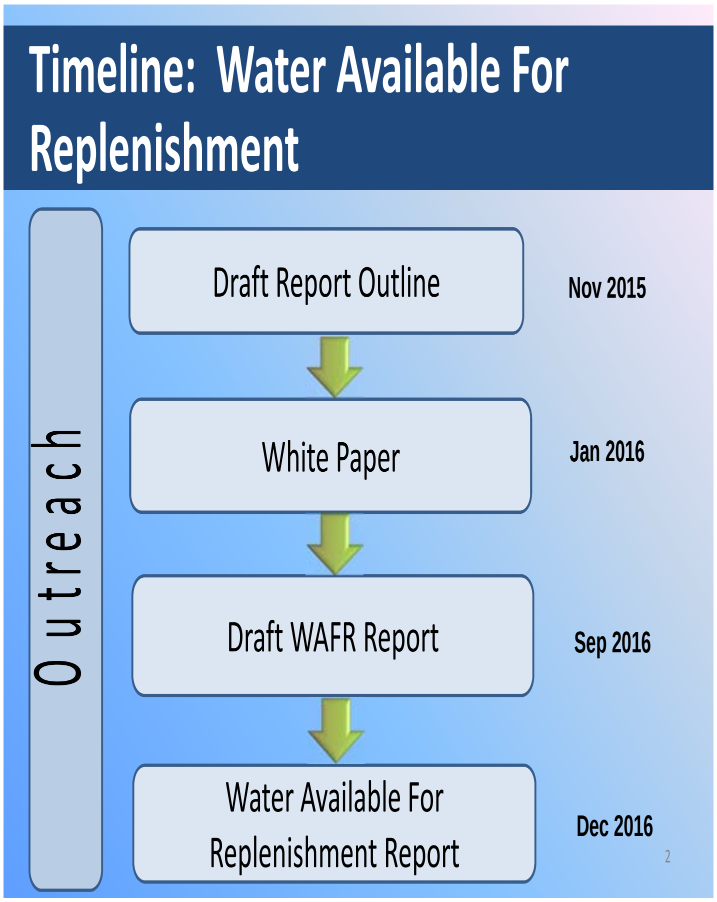

Figure 1. Timeline: Water Available for Replenishment Report

[7] Department of Water Resources. Water Available for Replenishment of Groundwater. PowerPoint presentation made by Rich Juricich. February 2, 2016.

Most of the technical work and writing of the draft report will be done by DWR staff, based on existing local and state information. Much of the information developed as part of the 2015 Update to the California Water Plan will be useful. Outreach with its SGMA advisory groups will continue through 2016 on this and other SGMA activities. DWR expects to brief the California Water Commission periodically through the year on progress and possibly some initial results.

CONCLUSIONS

SGMA requires that DWR adopt specific regulations and develop specific reports in support of local agencies developing groundwater sustainability plans to meet requirements of California's new groundwater law. Actions will be taken at the level of local groundwater basins, by local agencies. Actions are likely to include a combination of reduced or controlled future groundwater extractions and specific projects to add to groundwater storage. The December 31, 2016 report being developed by DWR will include essential water source and quantity information that will form the basis of specific project plans for additional local recharge programs.

This report is not being developed in a vacuum. A broad range of local agencies and advisory groups have been engaged with DWR since the summer of 2015, discussing what will be needed in this report that will be the most helpful to groundwater sustainability agencies as they put together their initial groundwater sustainability plans and plan for future recharge projects. The author will provide a fresh update on status of the WAFR report at the May 2016 USCID conference. In addition, a DWR speaker will provide updates on the overall SGMA implementation program including adoption of final GSP regulations.

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SACRAMENTO RIVER OPERATIONS AND DROUGHT MANAGEMENT — A SOLUTION FOR COMPETING DEMANDS

Angela Bezzone[1]
Anne Kwedar[2]

ABSTRACT

The following paper describes the efforts of the Sacramento River Settlement Contractors (Settlement Contractors) in coordination with the United States Bureau of Reclamation (Reclamation) to address the severe drought conditions experienced by the state of California during 2014 and 2015. Actions were taken to optimize the Central Valley Project (CVP) operations for multiple beneficial uses including water supply, fisheries, water quality, and waterfowl habitat. In 2014, the Settlement Contractors received a 75% Contract Supply (as required under the Settlement Contracts) for the first time since 1994. In an effort to maximize the available water supply and better align with the required timing of releases from Shasta Reservoir for fishery needs, the Settlement Contractors voluntarily committed to delay diversions and continued coordination with Reclamation throughout the irrigation season.

In 2015, following another dry winter, Reclamation and the Settlement Contractors continued their regular and frequent coordination to help ease the impacts of the depleted water supply. Based on observations from 2014, the State Water Resources Control Board and State and Federal fishery agencies provided Reclamation with additional direction and requirements for 2015 operations. Again, the Settlement Contractors voluntarily committed to extensive actions, which included efforts in addition to those undertaken during 2014. In order to assist the state in meeting the numerous competing demands, Settlement Contractors agreed to adaptively manage diversions throughout the year, assist in meeting critical needs within other areas through water transfers, and provide water for waterfowl habitat. The increased communication and flexibility throughout 2014 and 2015 required many creative solutions which may serve as valuable tools to address future water supply challenges. This paper will identify the various demands on the CVP and the efforts undertaken by the Settlement Contractors during a period of severe drought and competing water needs.

INTRODUCTION

Early in 2014, as the dry hydrologic conditions continued from prior years, Governor Jerry Brown proclaimed a State of Emergency. This proclamation on January 17, 2014 called for increased water conservation, implementation of water shortage contingency plans, expedited processing of water transfers, and consideration of impacts to endangered species. The lack of precipitation, low reservoir storage levels, and the

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Governor's proclamation, led to increased coordination and planning efforts across the state. In 2015, California entered its fourth consecutive year of below average rainfall and minimal snowpack. Throughout the state, the prolonged drought conditions created management challenges that were intensified by competing demands with each successive dry year. In the Sacramento River watershed, the United States Bureau of Reclamation (Reclamation) and the Sacramento River Settlement Contractors (Settlement Contractors) focused on actions to optimize the Central Valley Project (CVP) operations for multiple beneficial uses including water supply, fisheries, water quality, and waterfowl habitat.

WATER SUPPLY

In the Sacramento River watershed, water year types are classified by the Sacramento Valley Year Type Index. Figure 1 provides the Sacramento Valley Year Type Index classifications for 1906 through 2015. As shown in Figure 1, Water Year 2012 was classified as below normal, Water Year 2013 as dry, and Water Years 2014 and 2015 as critical.

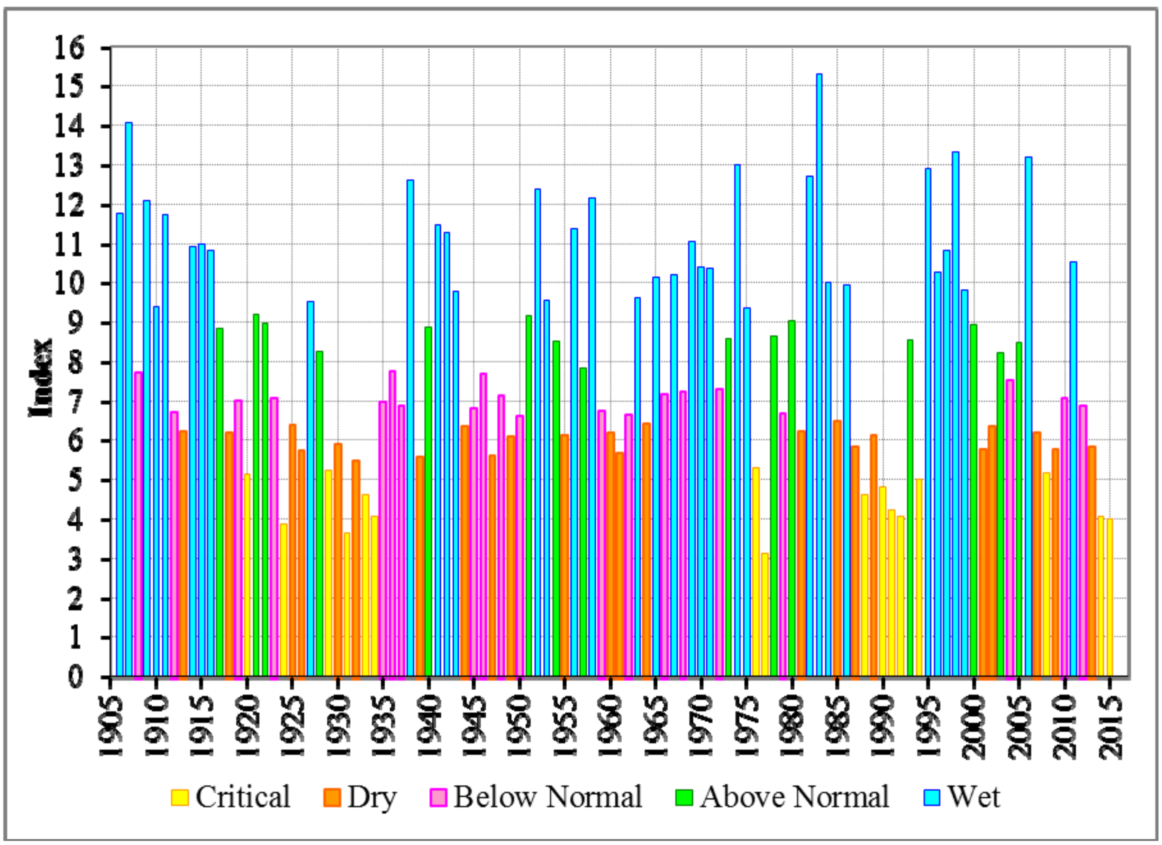

Figure 1. Sacramento Valley Year Type Index

Governor Brown's State of Emergency proclamation directed the State Water Resources Control Board (SWRCB) to notify water right holders statewide of the water shortage and the potential for curtailment of diversions authorized under their appropriative water rights due to the drought conditions. Curtailment of diversions under post-1914 water rights was in effect during the majority of the 2014 and 2015 irrigation seasons. Furthermore, during the summer of 2015, Notices of Unavailability were issued to many senior water right holders with pre-1914 claims. These notices were to inform the pre-1914 claimants that water may be unavailable for appropriation under their asserted water rights. The unavailability of water for diversion by many water right holders created a large deficit in water supply statewide.

The lack of precipitation resulted in low reservoir storage levels in reservoirs throughout California. The peak storage in Shasta Reservoir occurred during April in both years and was 2.4 million acre-feet in 2014 and 2.7 million acre-feet in 2015, 61% and 69% of average, respectively, for that time of year.

WATER DEMANDS

Shasta Reservoir is the largest reservoir in the CVP and is operated by Reclamation. Water stored in Shasta Reservoir is used to meet multiple demands along the Sacramento River, in the Sacramento-San Joaquin Delta (Delta), and outside of the Sacramento River watershed through export facilities located in the southern Delta. These demands include agricultural water supplies, municipal and industrial water supplies, cold water and appropriate flows for fish, water for managed wetlands, and water quality. The CVP and State Water Project (SWP) operate under a Coordinated Operating Agreement (COA) dated November 24, 1986 to balance the responsibilities of the CVP and SWP meeting these objectives.

Agricultural Demands

The Settlement Contractors hold water rights, mainly for irrigation of agricultural lands, along the Sacramento River which have area of origin protection or are senior to Reclamation's water rights for Shasta Reservoir. These downstream water right holders filed protests to Reclamation's applications for water rights to operate Shasta Reservoir. In order to dismiss these protests, Reclamation executed settlement contracts with these water right holders (Settlement Contracts) in 1964. The purpose of the Settlement Contracts was to settle water right issues along the Sacramento River to allow for the development of the CVP (including Shasta Reservoir) and establish terms for the diversion of water from the Sacramento River and its tributaries by the Settlement Contractors. Prior to execution of the Settlement Contracts, extensive research was conducted to determine the extent of each Settlement Contractor's water rights. The average yield of these water rights was considered to arrive at monthly Base Supply quantities in the Settlement Contracts, and additional Project Water (as defined in the Settlement Contracts) was included based on estimated/projected average deficiencies above the yield of the water rights. For the purposes of this paper, the combined monthly Base Supply and Project Water quantities are referred to as Contract Supply. The Settlement Contractors divert under their individual water rights at times when flows in the Sacramento River are adequate to meet their demands. However, the Settlement Contracts provide a reliable water supply from Shasta Reservoir during times when natural flows in the Sacramento River are insufficient (i.e., during times of curtailment of water rights by the SWRCB).

Pursuant to the terms of the Settlement Contracts, Contract Supplies are subject to a 25% reduction during water years classified as “Shasta Critical.” A Shasta Critical Year is determined based on the actual and forecasted unimpaired inflow to Shasta Reservoir as set forth in the Settlement Contract. In general, a Shasta Critical Year occurs when the forecasted unimpaired inflow to Shasta Reservoir is less than 3.2 million acre-feet (MAF); however, the minimum required unimpaired inflow may increase up to 4.0 million acre-feet depending on deficiencies in prior years. Figure 2 identifies the unimpaired inflow to Shasta Reservoir for 1964 through 2015. Since the first Settlement Contracts were executed in 1964 there have been six Shasta Critical Years (1977, 1991, 1992, 1994, 2014, and 2015). Because 2014 and 2015 were both Shasta Critical Years, the Settlement Contractors were authorized to divert only 75% of their Contract Supplies.

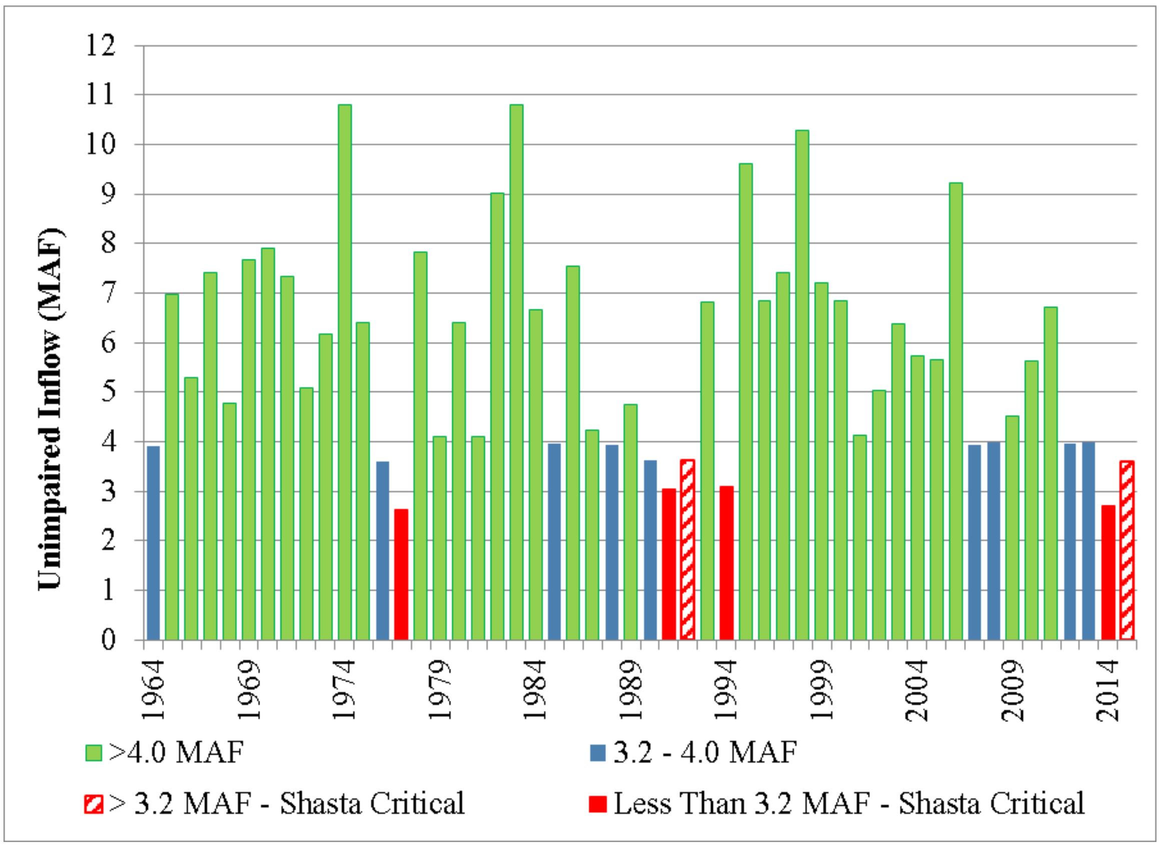

Figure 2. Observed Unimpaired Inflow to Shasta Reservoir 1964-2015

Water from the CVP and Shasta Reservoir is used to provide water supply under San Joaquin River Exchange Contracts for use in the San Joaquin Valley. The San Joaquin River Exchange Contractors are water right holders on the San Joaquin River senior in priority to the CVP. They receive supplies from the CVP, including Shasta Reservoir, in exchange for their rights to San Joaquin River flows for the benefit of the CVP. The San Joaquin River Exchange Contractors’ supplies are subject to the same reductions as the

Settlement Contractors and based on Shasta Reservoir unimpaired inflow, similar to the Settlement Contractors.

Reclamation also provides agricultural water supplies under its water rights for Shasta Reservoir to CVP Water Service Contractors located both upstream and downstream of the Delta. The CVP Water Service Contractors hold contracts with Reclamation for CVP Project Water and divert water from the Sacramento River or receive water exported from the Delta. The quantities delivered under these contracts are discretionary and based on hydrologic conditions and other regulatory constraints; therefore, allocations can be as low as 0% in a given year. Allocations to CVP Water Service Contractors north and south of the Delta were 0% in 2014 and 2015.

Water Quality and Environmental Demands

Environmental concern and uncertainty has risen over the years resulting in numerous actions by the SWRCB, fishery agencies, and others. Many new requirements have been placed on reservoir operations to provide water supplies for water quality and/or environmental needs, including protection of species and their habitat. In the Sacramento River and Delta watershed, new instream requirements have been implemented since the construction of Shasta Reservoir, which affect operations within the entire CVP.

In 1960, Reclamation entered into a Memorandum of Agreement (MOA) with California Fish & Game, the predecessor to the California Department of Fish & Wildlife (DFW), to establish flow objectives in the Sacramento River for the protection and preservation of fish and wildlife resources. These objectives included a minimum release at Keswick Reservoir (the afterbay of Shasta Reservoir) from September through the end of February in all water years and requires releases during September 1 through December 31 be made with minimum fluctuations to protect salmon.

In 1990 and 1991, the SWRCB issued Water Right Orders 90-05 and 91-01 modifying Reclamation's water rights for the Sacramento River to operate Keswick and Shasta Dams and the Spring Creek Powerplant to meet a daily average water temperature of 56°F as far downstream in the Sacramento River as practicable during periods when higher temperatures would be harmful to fisheries. The established downstream control point is the Red Bluff Diversion Dam (RBDD); however, the orders allow for the water temperature compliance point to be modified when the objective cannot be met at RBDD[3]. Each year, a Sacramento River Temperature Task Group (SRTTG) devises operation plans to provide the best protection consistent with the CVP's temperature control capabilities, considering the annual needs and seasonal spawning distribution monitoring information for winter-run and fall-run Chinook salmon. In addition, Order 90-05 modified the minimum flow requirements initially established in the 1960 MOA for the Sacramento River below Keswick Reservoir, and the orders recommended the construction of a Shasta Temperature Control Device (TCD) to improve the management of the limited cold water resources. Installation of the TCD was completed in 1997.

[3] For the purpose of this paper, the Upper Sacramento River refers to the portion of the Sacramento River upstream of the temperature compliance point.

In addition to operations at Shasta Reservoir, the CVP also must assist with meeting certain objectives in the Delta. As stated in the Water Code, "The SWRCB is responsible for the regulation of activities and factors which may affect the quality of waters of the state". Under this authority the SWRCB adopted the 1995 Bay-Delta Water Quality Control Plan (WQCP) to establish water quality objectives to contribute to the protection of beneficial uses including municipal and industrial, agriculture, and fish and wildlife. The WQCP became the basis for SWRCB Decision 1641 and Revised Decision 1641 (D-1641), which implements the objectives of the WQCP by imposing water quality and flow requirements on the CVP and SWP Delta operations. D-1641 includes export restrictions, minimum Delta outflow, and flow objectives for fish and wildlife beneficial uses within the Delta. These objectives are met by operations of the CVP, SWP, and other water right holders.

In addition to the requirements under D-1641, the operation of the CVP is subject to other environmental requirements. Under the Federal Endangered Species Act, Reclamation consults with the U.S. Fish and Wildlife Service (USFWS) and the National Oceanic and Atmospheric Administration (NOAA) Fisheries to avoid jeopardizing listed species or adversely modifying their critical habitat. The long-term operations of the CVP and SWP are subject to the USFWS's biological opinion issued in 2008 (2008 BiOp) and NOAA's National Marine Fisheries Service's (NMFS) biological opinion issued in 2009 (2009 BiOp). The 2008 BiOp includes reasonable and prudent alternatives to minimize impacts to the Delta smelt, a federally endangered species, by limiting diversions at the export facilities when conditions exist which may negatively impact the Delta smelt. The 2009 BiOp includes reasonable and prudent alternatives to minimize impacts to other federally listed species including the Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, Central Valley steelhead, and the Southern Distinct Population Segment of North American green sturgeon, by maintaining sufficient carryover storage and optimizing use of cold water pools.

The coordination of operations on the Sacramento River during 2014 and 2015 was initiated for the purposes of assisting with efforts toward the protection of winter-run and spring-run Chinook salmon through temperature management for Shasta Reservoir and the Upper Sacramento River. In addition, extensive coordination occurred between Reclamation, the Department of Water Resources (DWR), and other agencies for the purpose of Delta operations including protection of Delta smelt, D-1641 requirements, and through-Delta water transfers.

2014 SACRAMENTO RIVER OPERATIONS

Water Supply Outlook

After a dry 2013, Water Year 2014 started out with record-breaking low precipitation during December and January. In response to the drought conditions, on January 29, 2014 Reclamation and DWR submitted a Temporary Urgency Change Petition (TUCP) to the SWRCB requesting temporary changes to the requirements in their water rights for the CVP and SWP. This request to modify Delta water quality objectives included changes to Delta Outflow, Delta Cross Channel (DCC) Gate closures, and export limitations contained in D-1641 during the spring months. The TUCP was approved by and order issued by the SWRCB. As the drought year progressed, Reclamation and DWR made several additional requests to the SWRCB to modify various requirements of D-1641. The SWRCB required increased consultation with SWRCB staff and fishery agencies (including DFW, NOAA Fisheries, and USFWS) and additional reporting and planning requirements as a result of the TUCP. As such, Reclamation's drought planning, modeling efforts, and operations became subject to increased scrutiny and heightened environmental concerns.

On February 15, 2014, the Settlement Contractors received a letter informing them of the current critical water supply conditions and availability as a result of the drought. Following Reclamation's notification, the Settlement Contractors initiated discussions with Reclamation and offered technical assistance and coordination to maximize the beneficial use of available water supply to the extent possible. On March 3, 2014, storage in Shasta Reservoir was approximately 1.8 million acre-feet, or approximately 54% of average for that time of year, and initial allocations to CVP Water Service Contractors were forecasted to be 0%.

In April 2014, as part of the TUCP approvals, Reclamation and DWR developed a Drought Operations Plan (DOP) in coordination with the fishery agencies. The DOP identified proposed operations for April through mid-November including potential changes to the SWRCB's TUCP Order and modifications to ESA requirements. The purposes of the DOP were to balance all needs, specifically to provide essential human health and safety needs, control saltwater intrusion in the Delta, preserve cold water in Shasta Reservoir to maintain cold water temperatures in the Sacramento River for salmon, and protect endangered species and other fish and wildlife resources.

Pursuant to the Settlement Contracts, 2014 was classified as a Shasta Critical Year, and the Settlement Contractors were subject to a 25% reduction of their Contract Supplies. The SWRCB curtailed diversions under all post-1914 water rights in the Sacramento River watershed beginning on May 27, 2014. This action curtailed many of the Settlement Contractors' underlying water rights; however, the Settlement Contractors continued diversions as authorized under the Settlement Contracts and through extensive coordination with Reclamation. The 2014 curtailment remained in effect through mid-November 2014.

Coordination

Following Reclamation's initial notification to Settlement Contractors in February 2014, hydrologic conditions marginally improved and the Settlement Contractors began efforts to evaluate technical details used by Reclamation in forecasting models. Within these forecasts were gross estimates for inflows and outflows between gaged locations within the Sacramento Valley (the difference of which is referred to as accretion/depletion). These estimates were based on historical gage data. The Settlement Contractors worked closely with Reclamation to disaggregate the Settlement Contractor and Tehama-Colusa Canal Authority (TCCA) diversions from the gross estimate as known depletions and to develop a more realistic forecast of accretion/depletion for 2014. The result of this analysis demonstrated there was adequate supply to meet the Settlement Contractors' 75% Contract Supply and meet Reclamation's other obligations.

In accordance with the Settlement Contracts, Reclamation confirmed a 75% water supply to the Settlement Contractors and stated in an April 18, 2014 letter to the Settlement Contractors, "the continued drought and unique hydrology [made providing a 75% supply] difficult and has forced Reclamation and the Sacramento River Settlement Contractors to explore creative solutions." This coordination and the resulting solutions are described below.

Early spring coordination between the Settlement Contractors and Reclamation resulted in concepts to manage the stored water supply in Shasta Reservoir. The Settlement Contractors voluntarily committed to shift their diversion pattern to better align with the timing of releases for fishery needs. Settlement Contractors developed reduced diversion schedules with delayed April and May diversions for planting of rice until later in the season. By delaying planting, this shifted the highest crop demand to later in the season. This was a major risk to farmers as it could result in reduced crop yields and postpone harvest. With increased potential for precipitation later in the fall, the postponed harvest could increase costs and further reduce crop yields.

Due to efforts undertaken by Settlement Contractors to reduce and minimize diversions during April and May 2014, Reclamation allowed the rescheduling of Base Supply not diverted in April and May into later months, including the Critical Months that primarily comprise July, August, and September for the majority of Settlement Contractors. This provided flexibility to adjust to the shifted planting and diversion season. Overall, Settlement Contractors diverted approximately 29%[4] less than their combined total 75% Contract Supply for April and May. By delaying diversions in April and May, Reclamation was able to conserve additional storage in Shasta Reservoir to benefit the cold-water pool and the Upper Sacramento River temperature management operation for fishery needs.

Regular and frequent coordination between the Settlement Contractors and Reclamation continued throughout the spring of 2014 to assist Reclamation in managing flows of the Sacramento River and ensure a physical water supply for Settlement Contractors while optimizing benefits to the fisheries. In addition to weekly meetings with Reclamation, Settlement Contractors met with members and staff of the SWRCB, NMFS, DWR, and other CVP Water Service Contractors to discuss 2014 operations, including the technical details of Reclamation's forecast modeling, diversion scheduling, and Sacramento River temperature planning.

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[4] Based on diversions by a group of Settlement Contractors representing approximately 88% of water supply available under all agricultural Settlement Contracts.

Water Transfers

Following initial allocations of 0% to CVP Water Service Contractors, the San Luis & Delta-Mendota Water Authority (SLDMWA) and TCCA began conversations regarding water transfers with many Settlement Contractors. Reclamation agreed to execute Forbearance Agreements to facilitate the transfer of a portion of Settlement Contractors' Contract Supplies to CVP Water Service Contractors. The participating Settlement Contractors transferred a total of approximately 62,000 acre-feet through crop idling/crop shifting and approximately 51,400 acre-feet through groundwater substitution to areas in need of water supplies. After accounting for losses and considering demands, approximately 35,500 acre-feet was delivered to TCCA, which diverts from the Sacramento River near Red Bluff, on a pattern similar to which it was made available.

The total quantity of surface water made available by participating Settlement Contractors for use within SLDMWA under the 2014 Forbearance Agreements was 70,535 acre-feet. SLDMWA receives water from the export facilities located in the Delta. Water transfers involving conveyance through the Delta typically occur within the operational parameters of the 2008 BiOp on the Continued Long-Term Operations of the CVP/SWP (i.e., transfer water is typically conveyed through the Delta during July through September), or as amended through coordination and consultation with USFWS and NMFS. Initially, conveyance of surface water made available pursuant to the 2014 Forbearance Agreements was to occur prior to the end of September 2014; however, this was not possible due to the restrictive conveyance operations that were required to address worsening drought conditions and cold-water pool management at Shasta Reservoir.

To facilitate transfers to SLDMWA, Reclamation entered into consultations with USFWS and NMFS. This included submittal of modifications to the CVP and SWP DOP and operational forecasts to describe the proposed drought response measures and the extension of the period during which transfer water may be pumped from the Delta at the CVPS's Jones Pumping Plant. Reclamation received concurrence from the USFWS and NMFS that the proposed modified drought response actions had roughly equivalent effects to Delta smelt as compared to the actions previously analyzed and would be within the incidental take authorized by the 2008 BiOp. Therefore, water to be delivered to SLDMWA was released at a time which coincided with fishery needs along the Sacramento River.

Outcome

Settlement Contractor actions maximized flexibility in their operations to support Reclamation's drought operations throughout 2014. The Settlement Contractors met the delayed spring diversion schedule and successfully implemented water transfers to areas in need of critical water supplies, both of which had beneficial impacts to the Sacramento River fishery. Reclamation met the temperature objectives on the Sacramento River set by the SRTTG through mid-August. The real-time decision making, increased coordination between competing demands, and regulatory flexibility were crucial in the operation of the CVP during 2014. The major lessons learned in 2014 were to become initial guidelines for drought planning in 2015.

2015 SACRAMENTO RIVER OPERATIONS

Water Supply Outlook

Governor Brown issued Executive Order B-28-14 on December 22, 2014, which expanded his previous proclamations and extended them through the spring of 2016. California was entering its fourth year of below-average rainfall and very low snowpack. Anticipating severe drought conditions to continue, DWR and Reclamation coordinated with USFWS, NMFS, and DFW to create a 2015 Drought Contingency Plan (2015 DCP) which was provided to the SWRCB in mid-January. Reclamation again committed to working closely with the Settlement Contractors to minimize Keswick Reservoir releases prior to the start of the temperature management season in late May. The 2015 DCP included an analysis based on water supply forecasts and required responses. As a result, Reclamation and DWR submitted a TUCP to the SWRCB on January 23, 2015 to request modification of D-1641 consistent with the 2015 DCP. The TUCP requested a change to Delta outflow requirements and export rates in an effort to balance competing demands for beneficial uses.

On February 27, 2015, Reclamation announced the initial 2015 allocations for the CVP. Reclamation stated that based on low forecasted unimpaired inflow to Shasta Reservoir, 2015 was projected to be a second consecutive Shasta Critical Year. Initial allocations to CVP Water Service Contractors were again forecasted to be 0%. On April 1, 2015, the Governor issued Executive Order B-29-15 which acknowledged the continued enormity of the drought.

The Settlement Contractors received an updated letter from Reclamation on April 15, 2015 informing them of the 75% Contract Supply but, due to worsened drought conditions, it was contingent on continued and increased cooperation and flexibility as compared to 2014. This flexibility included scheduling diversions in coordination with fishery releases, making resources available for real-time fish monitoring, pursuing water transfers, using groundwater wells to supplement surface water diversions from the Sacramento River, and coordinating closely with refuge managers to re-time deliveries to wildlife refuges.

In 2015, diversions under post-1914 water rights in the Sacramento River watershed were curtailed by the SWRCB beginning May 1, 2015. Due to the extremely low snowpack, the drought conditions became more widespread in spring 2015 and the SWRCB issued Notices of Unavailability to numerous senior water users with pre-1914 claims. These Notices of Unavailability were issued in mid-June to many claimants along the Sacramento River and in the Delta which remained in place until mid-September 2015. The curtailments of diversions under post-1914 water rights were lifted in late October or early November, depending upon the priority of the right.

Coordination

In the spring of 2015, the Settlement Contractors worked closely with Reclamation to voluntarily shift diversion patterns to better align with the timing of releases from Shasta Reservoir and Keswick Reservoir for fishery needs. The Settlement Contractors developed estimated diversion schedules with the goal to delay and minimize diversions for crops. In consideration of and support for this agreement, Reclamation agreed to administer the accounting of the Settlement Contracts in a more flexible manner. As in 2014, due to the effort undertaken by the Settlement Contractors to reduce and minimize diversions in April and May, Reclamation allowed the flexibility of rescheduling of Base Supply not diverted in April and May into later months.

Settlement Contractors provided daily diversion schedules to Reclamation on a regular basis and held weekly coordination calls to closely monitor Keswick Reservoir releases, Sacramento River flows, and diversions, while making adjustments as necessary. By delaying diversions from April and May, Reclamation was able to hold water in Shasta Lake to benefit the cold water pool and temperature management on the Upper Sacramento River. Overall, Settlement Contractors diverted approximately 23%[5] less than their combined total 75% Contract Supply for April and May. In addition, Sacramento River flows were monitored on an hourly basis to target levels at various locations, including Wilkins Slough, to avoid de-watering pumps, provide inflow to the Delta for salinity control, and track the movement of transfer water.

Diversion scheduling and weekly coordination calls continued throughout the summer months as Keswick Reservoir releases were severely limited by the SWRCB. Pursuant to an Order by the SWRCB, Keswick Reservoir releases were restricted to about 7,250 cfs during June, July, and August which resulted in historically low Sacramento River flows. The Settlement Contractors responded in various ways in order to assist in meeting the numerous competing demands within the limited Keswick Reservoir releases. The Settlement Contractors reduced their collective June and July peak diversions and monitored Sacramento River flows on a daily and hourly basis. In order to minimize diversions and adapt to the historical low flow and level of the Sacramento River, Settlement Contractors maximized recapture efforts within irrigation systems and used available Settlement Contractor groundwater wells to supplement surface water supplies. The Settlement Contractors also reached out to individual landowners regarding the use of their groundwater wells to meet the demands of crops already planted. Quantities of groundwater pumped voluntarily by the Settlement Contracts and landowners to reduce diversions from the Sacramento River were in addition to the groundwater agreed to be pumped for water transfers. Also, many Settlement Contractors made decisions to prohibit planting of a double crop regardless of double cropped fields being included in an original crop plans.

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[5] Based on diversions by a group of Settlement Contractors representing approximately 88% of water supply available under all agricultural Settlement Contracts.

Water Transfers

Several Settlement Contractors agreed to pursue water transfers to areas of critical need through crop idling/crop shifting and groundwater substitution to further reduce spring diversions at the request of the SWRCB. As a result, these Settlement Contractors transferred a total of approximately 134,000 acre-feet through crop idling/shifting and 73,000 acre-feet through groundwater substitution, before accounting for losses, to areas in need of water supplies including SLDMWA, the East Bay Municipal Utility District (EBMUD), and the TCCA. This willingness to assist other areas of need together with reduced and rescheduled diversions facilitated Reclamation making a 75% Contract Supply available, consistent with the Settlement Contracts.

Water was delivered to TCCA on a pattern similar to which it was made available. However, water made available to EBMUD and SLDMWA was held in storage at Shasta Reservoir in an effort to benefit the cold water pool. The transfer water was delivered to EBMUD and SLDMWA at a time when the releases coincided with fishery needs along the Sacramento River, which is discussed further below.

Fall Water & Waterfowl Habitat

In early September 2015, Reclamation informed the coordinating Settlement Contractors that the fishery agencies were concerned with temperature issues in the Upper Sacramento River for the fall months, which resulted in Reclamation again changing the schedule of releases from Keswick Reservoir. At the time, Reclamation identified the majority of the surface water made available through the previously mentioned water transfers to EBMUD and SLDMWA was held in Shasta Reservoir. Reclamation's goal was to deliver this transfer water throughout the month of October. With the adjusted Keswick Reservoir release schedule, Reclamation informed the Settlement Contractors that diversions during October (primarily for rice straw decomposition and waterfowl habitat) represented a risk to the delivery of transfer water under contract with EBMUD and SLDMWA.

Reclamation requested the Settlement Contractors minimize or eliminate diversions from the Sacramento River during October to the extent possible. In return for minimizing October diversions and as an attempt to provide for as much migratory bird habitat as possible, Reclamation provided the flexibility to allow Settlement Contractors to divert water outside of the Settlement Contract season of April through October. Participating Settlement Contractors were authorized to divert remaining Contract Supplies (that would have otherwise been diverted in October) from November 1 through December 10, 2015 at a relatively constant rate to fields and habitat areas in order to optimize flooded lands, which provide valuable nourishment for migratory birds. Eight Settlement Contractors provided Reclamation with an estimated schedule of minimal diversions for October and quantities to instead be diverted during November 1 to December 10. Reclamation limited the total rescheduled quantity to 50,000 acre-feet for the participating Settlement Contractors and provided final response letters at the end of October following completion of an Environmental Assessment and Finding of No Significant Impact. The eight Settlement Contractors reduced October diversions and continued to divert into November and early December as agreed, resulting in almost 50,000 acres of flooded lands.

Outcome

Settlement Contractors optimized flexibility in their actions to support Reclamation's drought operations throughout 2015. The Settlement Contractors met the delayed spring diversion schedule, successfully implemented water transfers to areas in need of critical water supplies, reduced peak summer diversions, maximized recapture efforts, used available Settlement Contractor groundwater wells, reached out to individual landowners to use groundwater wells to meet their own demands, and adjusted fall diversions to optimize flooded lands for waterfowl habitat. Reclamation met the temperature plan for the Upper Sacramento River set by the SRTTG throughout the temperature management season.

Even with the numerous and extensive actions identified above, due to the reduced releases from Keswick Reservoir, Settlement Contractors experienced issues during the summer of 2015. The Settlement Contractors experienced reductions in diversion capabilities, increases in energy costs to divert water (for both surface water diversions and groundwater pumping), and in some cases, complete inability to pump from the Sacramento River due to low flows.

CONCLUSION

Throughout 2014 and 2015, the Settlement Contractors successfully coordinated with Reclamation to manage diversions along approximately 240 miles of the Sacramento River. In addition, diversions upstream of Wilkins Slough were monitored on a daily basis for 466 days over the two years. Overall, due to the drought conditions and flows on the Sacramento River, Settlement Contractors diverted approximately 80% and 78% of their authorized Contract Supply[6] of 75% during 2014 and 2015, respectively.

The Settlement Contractors have committed their available resources to improve environmental conditions along the Sacramento River. Over the years, Settlement Contractors and others have installed fish screens at their diversion facilities to protect fish from entrainment. Also, individual Settlement Contractors have undertaken various habitat improvement projects to benefit adult salmon spawning and juvenile salmon rearing. Most recently, these projects have included the restoration of Painter's Riffle located near the City of Redding and elimination of adult salmon passage through the Knights Landing Outfall Gates located near the town of Knights Landing. The recent drought has renewed and highlighted the Settlement Contractors' commitment to promote similar projects in the future to achieve multiple benefits.

[6] Based on diversions by a group of Settlement Contractors representing approximately 88% of water supply available under all agricultural Settlement Contracts.

As a result of the recent drought year challenges and need for increased communication, the Settlement Contractors are establishing a corporation for potential involvement by all Settlement Contractors to provide support, address common needs, and provide ongoing technical analysis. The increased communication and flexibility throughout 2014 and 2015 required many creative solutions which may serve as valuable tools to address future water supply challenges.

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FLUID WATER MANAGEMENT IN THE WESTERN U.S.

Brett Bovee[1]

ABSTRACT

The Western U.S. is continuing to experience important shifts in water management and planning that are focused on reallocating water between uses. This is being driven by a quantified awareness of our water supply limitations along with a need to provide water to new uses in response to economic, social, and political factors. While the development of new water supplies often attracts broad interest, it is actually both water demand management and water use reallocation that have been driving our ability to meet water demands over the last few decades, and available planning studies indicate that this is likely to continue. Available data suggests that we reallocate in excess of one million acre-feet each year in the Western U.S. as part of this new water management paradigm, and the data also show that our average annual reduction in diversions is even greater. To embrace the reality of this new style of water management, water managers should shift away from a check-box approach to water supply planning, and embrace water transfers and reallocation as one of the possibilities alongside water supply development and conservation. Some examples of this more active water management approach include rotational fallowing, groundwater banks, interruptible water supply agreements, and split season leases.

INTRODUCTION

Irrigated agriculture water uses represent the vast majority of water rights held in Western state appropriation systems, in part because there has been a long history of Federal programs to promote reclamation of Western lands, and irrigated farming was the dominant economic endeavor in many Western states for much of the twentieth century, as water resources were being developed and water rights were being claimed. The agricultural water rights that have been exercised for many generations are protected in many ways by the prior-appropriation doctrine. The prior-appropriation system of water rights continues to be viewed with scrutiny by those who see current water uses as sub-optimal from a social benefits perspective. This scrutiny has been particularly prevalent during times of drought and water supply shortage. Although research has been done looking at revised water allocation schemes, it is very likely that the prior-appropriation system will remain in place for the foreseeable future. Agriculture therefore finds itself at the heart of a conflict that will continue to persist and perhaps intensify in the future. In a very general sense and for certain geographic areas in the Western U.S., the conflict can be described as the allocation and use of limited water resources for agricultural uses that no longer represent the most valuable demand for the water, yet are maintained and protected by water rights laws and regulatory systems.

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While agriculture represents much of the history and culture of Western states, municipal and industrial growth has been a force of change. The Western states have seen the highest rates of growth in the U.S. over the past century, and the foundation of Western state economies has been shifting away from agriculture. Today, agriculture represents about 1.5% of Western states Gross Domestic Product, while it represented 4.7% in 1963.

To support this growth in the municipal and industrial sector, a range of activities are done to balance the new water demands with available water supplies. On the water supply side, there will likely always be a long list of potential water development projects which seek to provide an additional or expanded water supply from previously undeveloped or under-developed sources. These water supply projects include storage reservoirs, deeper groundwater wells, trans-basin diversions, desalination, and wastewater reuse. On the water demand side, an entire generation of Western citizens have grown up under the mantra of water conservation. In the municipal sector, water conservation has proven to be a worthwhile investment to reduce existing or projected water demands in the face of water supply limits. Some cities, such as Denver, treat and distribute less water now than they did in preceding decades, despite significantly larger populations served. Industries are also finding ways to reduce water demands through technological and process changes. Between water supply development and water demand management lies water use reallocation, in which an existing water use is transferred to an alternate water use. In most cases, water use reallocation happens in a market-based transaction, in which the use of a water right, which represents a form of property right, is sold or leased for payment. Reallocation might also take place due to regulatory or legal decisions, but these are less commonplace.

There are several water resource management realities that water managers at all scales of government and private industry will continue to grapple with in the near future. First, water supplies will likely be more limited and more variable under a changed climate, and also the limits of groundwater aquifer mining are becoming more evident and urgent. Second, municipal (and industrial) water demands are likely to continue to grow at regional scales even if water conservation and demand management initiatives are widely adopted, because of the underlying growth in population. Third, the opportunities for new water supply projects are somewhat limited due to high costs, permitting hurdles, and limited available water supplies. Given these realities, water market and transfer concepts have been and continue to be promoted throughout the Western U.S. as a legal and economical means of re-allocating water supplies to meet new uses and growth in certain sectors.

PAST WATER REALLOCATION

There is no easy way to accurately quantify how much water has been reallocated from one use to another in the Western states region, which is a result of our fairly localized management and administration of water resources, the undisclosed nature of many water right transfers, the myriad ways in which water is reallocated, and other factors. This section looks at two different datasets to attempt to quantify historical water use reallocation in the Western states. First, water use (diversion) data collected and compiled by the U.S. Geological Survey provides periodic snapshots of purposes for which water is used, and changes in those purposes are indicative of water use reallocation. Second, water right transaction data which has been collected and compiled by economic consultants provides a useful, yet incomplete, picture of water quantities transferred as property, which can be assumed to be largely indicative of water use reallocation.

USGS Water Use Data

The U.S. Geological Survey (USGS) has been tracking and publishing data on water uses since 1950, in a Circular report series that is published about every five years. From 1950 to 1980, the USGS water use data is provided at a state geographic level; while county-level data are available from 1985 to the most recent 2010 report. The USGS water use data elements and nomenclature have changed over the years. The primary data that have been consistently reported are diversion volumes for various types (purposes) of uses. Consumptive uses were reported from 1960 to 1995. Importantly, the USGS data continue to represent withdrawals of water, and have not included instream water uses such as those quantified in recent California water use reports.

Water use in the seventeen Western states has been dominated by irrigated agriculture. In 1960, irrigated agriculture made up 74% of total water diversions, with a total of 89.2 million acre-feet per year (Mafy). Irrigated cropland covered 35.7 million acres, for an overall Western states water duty of about 2.5 acre-feet per acre. In 2010, about 107 Mafy of water was diverted for irrigated agriculture, which represented about 65% of all recorded water diversions. The most recent Western region water duty is calculated as 2.3 acre-feet per acre, with 46 million acres of of irrigated cropland. In 1980, when water use peaked for the Western region, irrigation accounted for about 75% of all water diversions, and close to 90% of all water depletions (consumptive use), with an overall water duty of 3.2 acre-feet per acre. These trends in water use (as diversions) from 1950 to 2010 are shown in Figure 1.

The USGS water use data indicate several interesting trends. Perhaps the most interesting trend is the overall reduction in water diversions over the past 30 years, from a total water use peak in 1980 of 205 Mafy down to the most recent data point showing 166 Mafy of water use in 2010. This represents a decline of 39 Mafy or 19%. Agricultural water uses have dominated this water use reduction, with 46.7 Mafy of reduced irrigation diversions from 1980 to 2010. This water use reduction is reflective of substantial attention paid to demand management over the past 30 years or more, across all sectors of water use. Water conservation efforts have been very successful at reducing irrigation water diversions per unit of land, with the data showing a 28% reduction in overall water duty since 1980. Municipal sector water conservation efforts have also been successful, with per-capita municipal sector water use dropping 25% since 1980, from 240 to 181 gpcd. Population growth continues to push municipal sector water use upward, but the increase has been dampened by water conservation efforts.

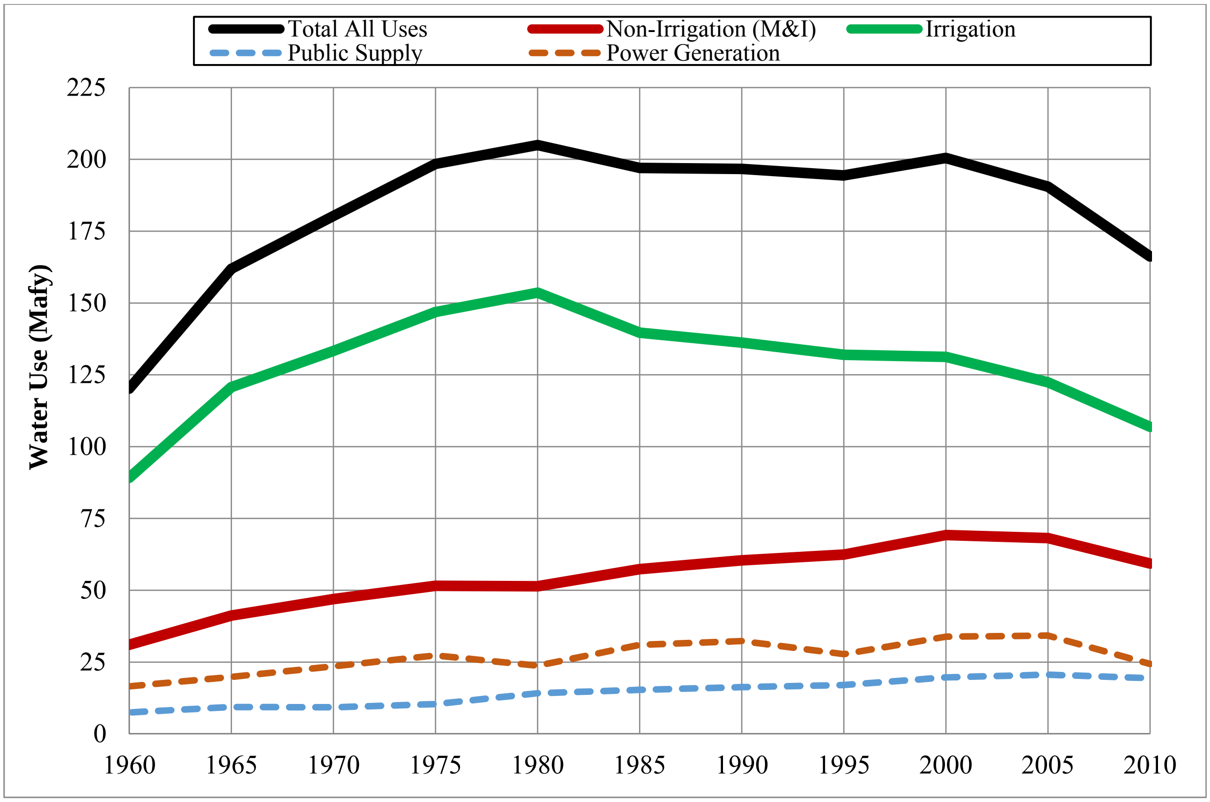


Figure 1. USGS Water Use Data for Western States, 1960-2010

A second trend is the continued growth in water use for municipal and industrial (M&I) uses. The M&I sectors have seen substantial growth as a percentage of water use, but the overall volumes remain less than agriculture. For this report, M&I water uses are quantified as all water uses except irrigation; which includes the following categories: public supply, domestic, livestock, aquaculture, industrial, mining, and thermos-electric power generation. M&I water uses have increased from 51.4 to 68.1 Mafy from 1980 to 2010. The growth in water use in the M&I sectors averaged 4.3% per year from 1955 to 1975, and 0.5% per year from 1980 to 2010.

Combining these two trends provides an indication of the volume of water (as diversions) that has been reallocated from irrigation to M&I use. The underlying assumption is that the increase in M&I sector water use came about because of the decrease in irrigation water use, as a result of direct and indirect water transfers. In other words, it is assumed that our available water supply in the Western states was a zero-sum game, such that an increase in one sector could only result because of a reallocation of water from a decrease in another sector. If this assumption is valid, then water use reallocation in the Western states can be calculated as 7.8 Mafy over the past 30 years, or an average of 260,000 afy of water rellocation each year. This calculation utilizes the smaller growth in the M&I sector water use, compared to the much larger reduction in irrigation water use, as a basis for quantifying reallocation.

For a variety of reasons, it is unlikely that this reallocation estimate is entirely accurate. Water supply development has taken place to serve new M&I water uses between 1980 and 2010. Some examples of this include new Bureau of Reclamation projects such as the Windy Gap Project in Colorado and the Navajo-Gallup Project in New Mexico; and also increased use of existing projects. Groundwater resources continue to be tapped for M&I water supplies, with the USGS data showing that about 40% of the 30-year growth in the M&I sector coming from new groundwater use. Except in areas of strict groundwater management, where impacts of groundwater pumping are mitigated, the increased in M&I water uses sourced from groundwater were not likely tied to an associated decrease in irrigation use. The USGS water use data also do not track instream flow uses, which have accounted for a substantial portion of the new water demands driving water use reallocation.

Water Transfer Data

Water rights are a usufructuary right, meaning that the right allows use of a water resource but not ownership of the resource itself. The use of water defined by a water right is often viewed as a property right in the Western U.S. and water right transactions are therefore considered a temporary or permanent transfer of property from one party to another. There is no comprehensive Federal or State-level database of water right transactions in the Western U.S. The multiple listing service (MLS) which forms the data backbone of real estate in the U.S. does not exist for water rights. Therefore, our view of water right transactions is limited to the efforts of private consultants in the area of water economics. From 1987 to 2009, Stratecon, Inc. published the *Water Strategist* and *Water Intelligence Monthly* which included a listing of known water right transactions in the Western states. The *Water Strategist* database has been the basis for several publications on Western water markets. For this paper, the *Water Strategist* data were obtained as the Water Transfer Database from the Bren School at UC-Santa Barbara. Since 2001, WestWater Research, LLC has maintained a similar database of water right transactions called *Waterlitix*. These two water transfer datasets are unique and independent, with different methods of data acquisition and different water transfer definitions.

A water right provides the owner with the ability to both divert water from a specified source and use the diverted water for a specific use. In some cases, the water right also includes a quantity of consumptive use, representing the extent to which the water right owner can use the diverted water without an obligation to return the water back to the hydrologic system. In many water right transactions, particularly for M&I sector uses, the buyer is interested in the quantity of consumptive use associated with the water rights being purchased. Therefore, water transaction data are often reported in volumetric units of consumptive use; unlike the USGS water use data which are reported in units of diversion.

As stated previously, most water right transactions are market-based, structured as either the permanent sale or temporary lease of the water right. The data for leases and sales are segregated because they obviously represent different forms of water use reallocation and each requires a different form of analysis when quantifying reallocation. The data were also filtered to remove water right transactions that were sold or leased to the same type of use as the original water right; providing a subset of water right transactions that represents a reallocation of water use. It was assumed that the entire volume of water involved in a permanent sale was actually transferred to the new (buyer) use at the time of the transaction. The reality is that M&I buyers often build water right portfolios well in advance of their need to utilize the purchased water supplies, and the water rights often remain in agricultural use for many years after the sale closes.

Figure 2 provides a graph of sales and lease transactions from 1987 to 2015. Water market activity experienced a notable decline in the years following the financial and real estate collapse in 2008, and the more recent data show that water market activity is still recovering. From 1990 to 2015, water transactions totaled an average of 1.3 Mafy, varying from a high of 2.4 Mafy in 2005 down to a low of 0.5 Mafy in 1996. Most of the transferred water was in the form of leases, accounting for an average of 1.1 Mafy or 84% of the total volume of water transactions. Similar to the USGS water use trends, the agricultural sector has been the source of water for most water right transactions. Agriculture was the preceding use in 70% of recorded transactions.

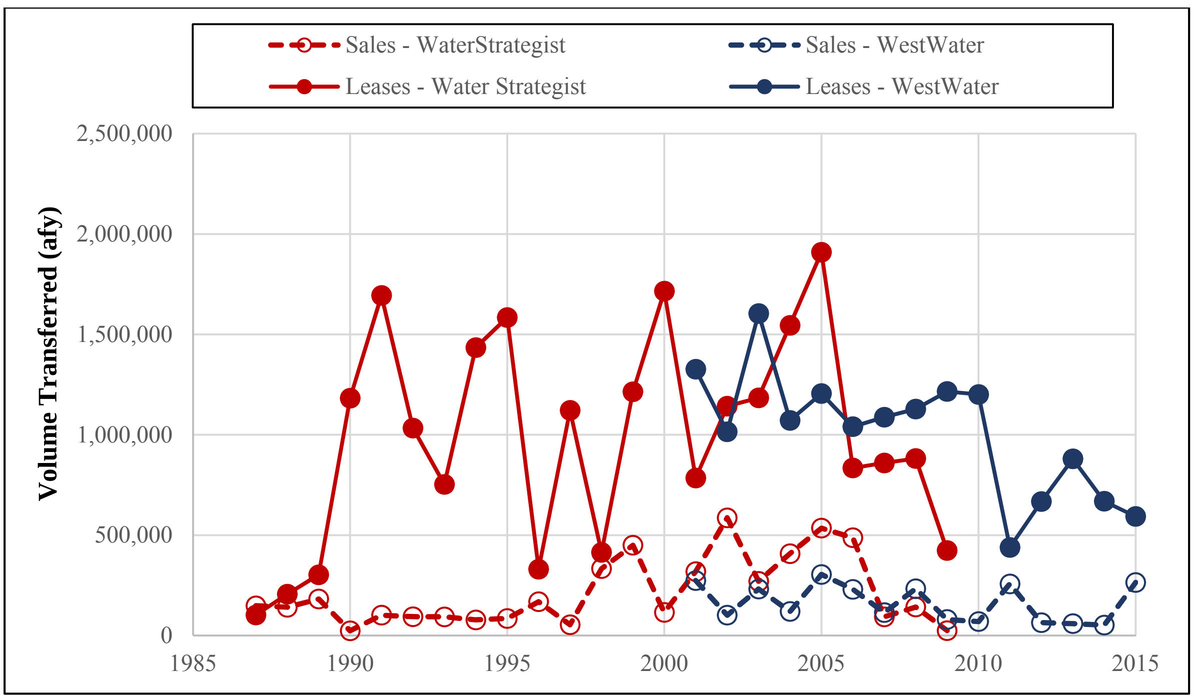


Figure 2. Water Transaction Data for Western States, 1987-2015

FUTURE WATER REALLOCATION

The two historical datasets present evidence that significant volumes of water are reallocated each year, either permanently or temporarily, from one use to another. The quantifications have known uncertainty, but point to a reality that reallocation of water between uses has been a significant trend in Western water resources management. And the future looks much like the past.

Water use forecasting is done in a variety of contexts. State water planning represents the sort of general, large-scale estimation of future water use that is useful for looking at water use reallocation. Not all Western states provide a quantified estimate of future water uses, but those that do provide data that indicate an expectation that water will continue to be reallocated from agriculture to M&I uses in water stressed areas. Figures 3 and 4 provide water use estimates for several Western states over a 30 to 50 year future time horizon. Similar to the assumptions applied to the USGS water use records, the changes in water use between sectors can be assumed to represent water use reallocation. The three states of AZ, CA, and CO all show a decline in irrigation water use and an increase in M&I water use; and the lessor of these two trends was assumed to represent a volume of reallocation. Collectively, these three states are projecting that an average of about 96,000 afy will be reallocated to new uses each year in the coming decades. A different forecast is made in the states of MT, OK, and WY. In each of these states, the estimated total future water use trend is slightly increasing, with no significant reduction in irrigation water use. While perhaps obvious, it is worthwhile to note that these three states have experienced a significantly lessor degree of water supply and demand imbalance in past years, and have also experienced less reallocation in the past.

WATER MANAGEMENT PARADIGMS

While a direct quantification does not exist, both the USGS water use data and the available data on water right transactions indicate that the reallocation of water between uses has been one of the focal points of water resource management over the past 30 years. Annual of transfers of over one million acre-feet per year between water uses are indicated by these datasets. The water transaction data further indicate that most of this water use reallocation occurs on a temporary basis as lease agreements. Contrary to these historical indicators, water supply planning is often viewed as a check-box approach wherein a water use entity forecasts long-term demands (or needs) and then seeks to compile a water supply portfolio that is capable of meeting the demands in full. This approach persists in many engineering plans, reports, and studies. The future for much of the Western U.S. might be a more dynamic framework in which a portion of the water supply portfolio is assembled on a short-term or flexible basis, in response to both immediate water demands and hydrologic conditions. This fluid water management structure is inherently more risky than the check-box approach, but it allows water use entities to invest less in uncertain long-term future water demand projections and it may provide a cost-effective alternative to expensive water supply development in water stressed areas. Water sharing arrangements may also help to reduce the permanent dry up of agricultural lands that serve as an important piece of rural Western economies.

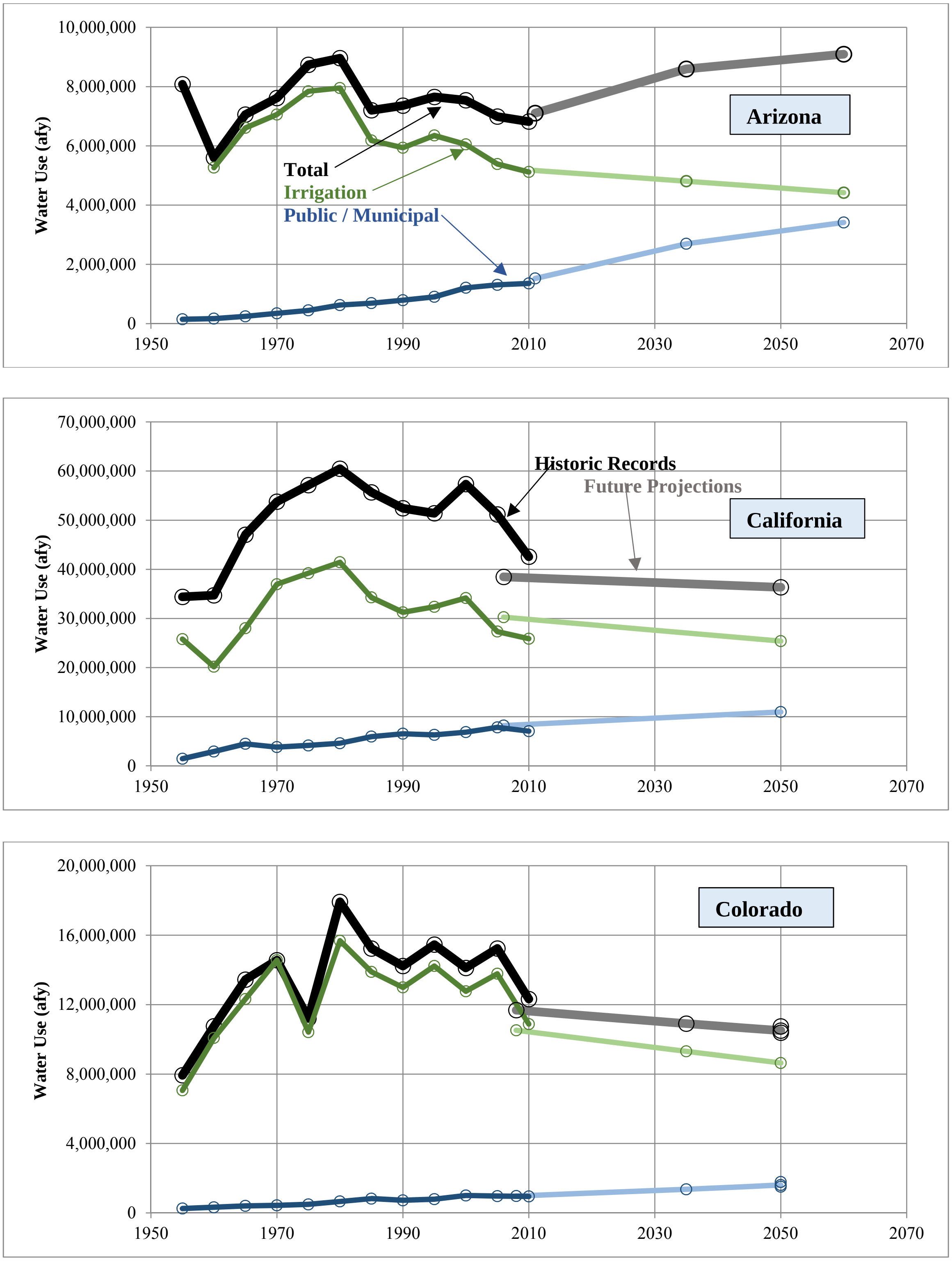
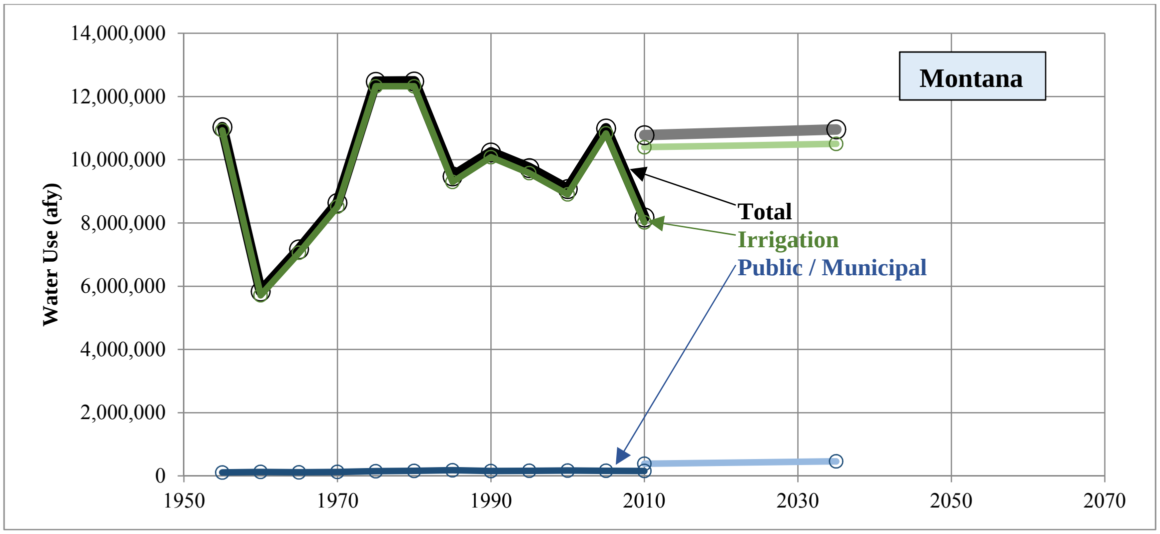
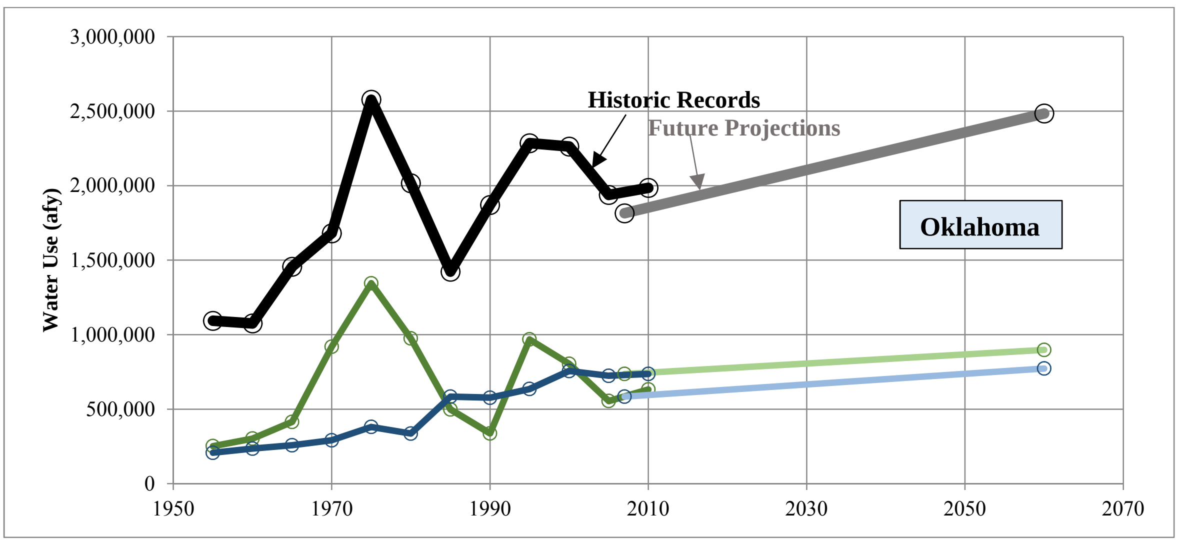


Figure 3. Historic and Future Water Uses for Three Water Reallocation States





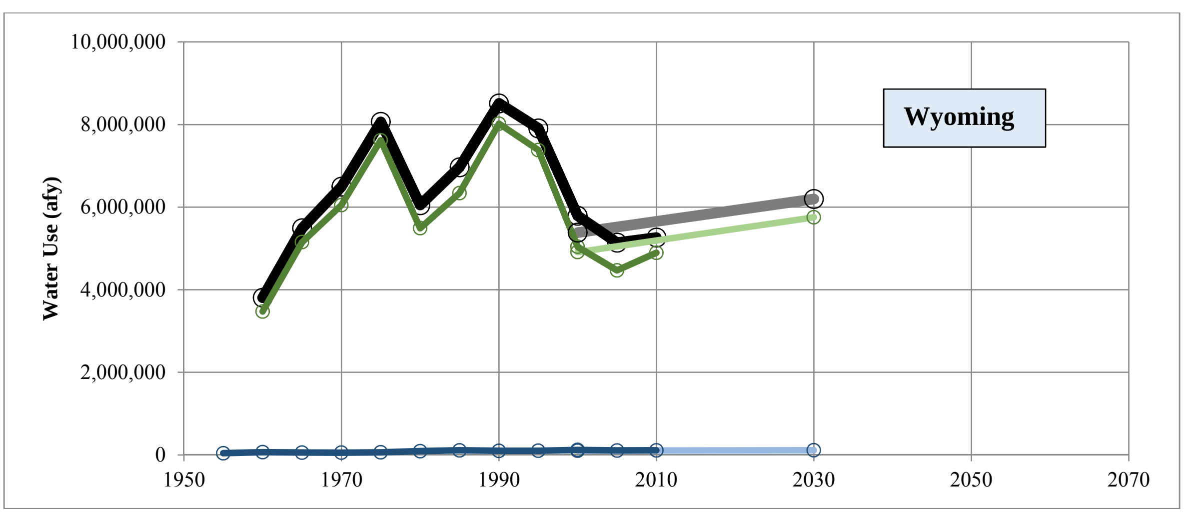


Figure 4. Historic and Future Water Uses for Three Water Development States

Several examples of fluid water management exist in the Western states. The Colorado Front Range provides one example. The water market of the Front Range is well developed and has historically been characterized by permanent sales of water rights from agriculture to M&I uses. Farmers in the region are aware of the risks faced by agriculture as communities continue to grow. An effort was launched by the Colorado Water Conservation Board in 2013 to study Alternative Transfer Methods (ATMs) and the recently released 2015 Colorado Water Plan defines a goal of having 50,000 afy of ATM projects in place by 2030. These ATMs are intended to reduce "buy and dry" of agriculture and instead provide flexible water sharing agreements between agriculture and M&I water uses. Colorado has clearly adopted a policy goal of increasing water sharing arrangements, in the hopes that it will help to preserve the agricultural economies of rural communities amidst the forces of municipal growth, as well as maintain agricultural lands as open spaces and community separators on the Front Range.

Another prominent example is found in the Southern California region, where most water users are faced with significant uncertainty in water supply reliability as evidenced by the 2014 and 2015 water years. Actions of municipal water providers illustrate the fluid nature of water management in this water-stressed region. The Mohave groundwater basin represents one of the most active water lease markets in the Western states, with an average of about 80 annual water trades. In this market, municipal water districts acquire water supplies on a short-term basis to cover immediate needs that are not met by alternative water sources. The Metropolitan Water District of Southern California (MWD) has also been an active lessor of water throughout the state, including in the Central Valley and Palo Verde Irrigation District. These Southern California water management entities have seemingly embraced a level of water supply risk and fluidity that would likely make many other Western U.S. water managers nervous, and anxious to secure more firm water supplies.

EXAMPLES OF NEW APPROACHES

There are several water sharing or transfer frameworks that are commonly looked to when evaluating alternatives to permanent water supply acquisition. The following paragraphs provide a few examples of these frameworks, while noting that others exist.

Rotational Fallowing

Rotational fallowing is a concept to allow a limited amount of water to be transferred out of a cohesive irrigated area without permanently impacting any of the participating farmland. Water is transferred to a provide for a new use, likely outside of the irrigated area, based on fallowing some of the irrigated acreage and transferring the consumptive use associated with the idle lands. The fallowing is temporary for each land parcel and the fallowed land is rotated back into crop production in a subsequent year. An example of this framework is the pilot project operated within the Yuma Mesa Irrigation and Drainage District (YMIDD) in southwest Arizona. Starting in 2013, the Central Arizona Groundwater Replenishment District (CAGRD) engaged in contract to lease Colorado River water from YMIDD generated from a voluntary rotational fallowing program.

Over the past three years, the pilot project has fallowed approximately 1,500 acres each year or 10% of the YMIDD farmland, generating 7,500 afy of Colorado River supplies for use by CAGRD. The intent of CAGRD is to utilize these water supplies to offset groundwater withdrawals, but to date the project water has been stored in Lake Mead as Intentionally Created Surplus. Other examples of rotational fallowing are found in the Palo Verde Irrigation District and the Imperial Irrigation District, both in Southern California.

Water Banks

A water bank is an administrative or regulatory entity created to facilitate the temporary transfer of water rights from those with available supplies to those with unmet demands. Water banks are intended to allow market transactions to occur faster and cheaper than they would as individual private water leases. Water banks can take on a variety of forms, but the basic concept allows water right holders to contribute all or a portion of their water supply to the bank while also allowing interested water users to rent banked water supplies for an established price. Usually, water banks cannot overcome the challenge that often accompanies water leases of potentially injuring other water rights; and therefore some form of regulatory approval is usually necessary for each rental out of a water bank. As a result, water banks function well when they utilize a uniform water resource such as an expansive groundwater aquifer or series of cooperatively managed storage reservoirs. Idaho has had a long history of operating water banks, with the first water bank established in 1937. Since 1979, the Upper Snake River water district, known as Water District 01, has operated a Rental Pool which allows transfers of storage water allocations held in several Bureau of Reclamation reservoirs. Storage rentals have varied considerably each year, with less rentals in dry years when irrigation districts who own the storage allocations need the supplemental water. Average annual rentals total 209,000 afy, varying from 9,900 afy up to 433,000 afy. Since 1998, the Rental Pool has been used to satisfy instream flow requirements for endangered salmon species through rentals to the Bureau of Reclamation, and this now forms the majority of annual Rental Pool activity. Rentals are also completed to satisfy Snake River mitigation obligations resulting from groundwater pumping by irrigation districts, for direct use by irrigation districts, and for hydropower generation. While the Rental Pool has provided an important water management function, its reliability as a water supply in dry years has been limited due to a fixed pricing structure, which is set by a Rental Pool committee as opposed to a competitive market.

Interruptible Water Supply Agreements

Interruptible water supply agreements (IWSAs) provide for the shared use of a water right. The intent of an IWSA is to preserve the original use of a water right, while also providing for a new use under temporary conditions. The water sharing structure of IWSAs can take many forms; such as a lease under certain hydrologic conditions, a fixed cyclical lease (3 out of 10 years for example), or a split-season lease. As with most water transfers, the original water right is typically for irrigation, and the new use is often for M&I or environmental flow purposes. The most realistic type of IWSA often relates to the type of cropping pattern under the original water right, with annual crops allowing year-to-year decisions before planting and perennial crops being more suited to split-season or longer period water sharing. Although not always referred to by the IWSA name, these types of flexible leasing agreements have been ubiquitous throughout the Western U.S. One example of an IWSA is found on the McKinley Ditch in southwest Colorado. The Colorado Water Trust recently purchased water rights and finalized a split-season lease agreement between a 214-acre hay ranch and the Colorado Water Conservation Board to provide late-summer instream flows in the Little Cimarron River. Western Rivers Conservancy owns the ranch will continue to operate it in most years, with hydrologic conditions determining when the ranch water rights will be left in the river as instream flows.

Efficiency Improvements

A final framework is one that often attracts a lot of interest because of the large fraction of water use that agriculture represents in the Western states. In a very general sense, an irrigation district or ditch company could improve the efficiency of water delivery from the water source to the farm turnouts, with the higher efficiency allowing either less water to be diverted at the source or more water available for delivery (to the farms or an alternate use). Looking at typical conveyance efficiencies on earthen canal systems, this concept seems plausible; however the reality is that such efficiency improvements often do not yield any water for transfer. The losses along an irrigation canal are mostly returned to the river source or some other water feature, and utilized by downstream entities. As a result, the conditions necessary for efficiency improvements to make sense from a water transfer or sharing perspective often involves the following: (1) a desire for increased instream flows, particularly in the river reach between the point of diversion and the location of return flows, or (2) a terminal basin in which the return flows resulting from canal losses are not utilized by a downstream entity. An example of irrigation efficiency improvements is found on the Verde River in Arizona. The Nature Conservancy helped to fund canal headgate automation and also provided incentive payments for reduced irrigation diversions, all of which have successfully increased instream flows in the Verde River while maintaining the original farming operations. Other irrigation efficiency project examples are found in the Imperial Irrigation District of Southern California and the Deschutes River in Oregon.

CONCLUSION

Most water rights and most water uses in the Western U.S. are agricultural, which is a reflection of the region’s history of water development and water right laws. As population in the West continues to grow, and as our economies and social values continue to change, new water demands are being placed on regional water supplies that are largely over-allocated and stressed. Historical data from the past 30 years of water uses and transfers shows that Western water managers have responded by employing water demand management and utilizing reallocation methods. It appears that the volumes of water that have been conserved and/or reallocated over the past 30 years are considerably larger than the volumes of new water supplies developed. Looking to the future, it is probably necessary for water managers in the Western states to continue to do more of the same, and to embrace a more fluid and dynamic approach in which flexible water transfers and conservation efforts are utilized alongside efforts to secure firm water supplies. A more fluid water management paradigm adds uncertainty and risk, but such risks are a likely to be a reality of Western U.S. water conditions in the 21st century. Fortunately, there are many successful examples of new approaches which aim to share water resources among various water users. Water banks, water markets, and fallowing agreements are as much a part of our vocabulary as reservoir storage and supplemental groundwater wells. Fluid water management is an important mindset to help ensure that the Western U.S. maintains a robust agricultural sector, and to meet the changing water demands that are certain to come in the years ahead.

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ADAPTING TO DROUGHT: ASSESSING AND CONTROLLING GROUNDWATER INTERFERENCE WITH SURFACE WATER IN OREGON

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ABSTRACT

The year of 2015 was a year of historical drought in Oregon and across the West. A winter with record-low or near-record-low snowpack across the state combined with below-average precipitation and above-average temperatures throughout the spring and summer resulted in dramatically lower surface water flows and drought disaster declarations by the U.S. Department of Agriculture for all Oregon counties. In southern Oregon, as this was the second or third year of drought, the impacts were intensified.

One of the most pressing issues with continued drought is the impact not only to surface water, but groundwater as well. When surface water resources are extremely low, as this past summer, groundwater is often tapped to supplement the dwindling surface water resources. However, the geology of Oregon is such that surface water and groundwater do not always exist as separate and distinct resources. These resources often interact in a complex matrix of underground aquifers.

The Oregon Department of Water Resources ("OWRD") has implemented administrative rules to govern groundwater interference with surface water in order to help administer water during times of scarcity. Division 9 of Chapter 690 of the Oregon Administrative Rules governs groundwater interference with surface water. These rules are designed to establish criteria to guide OWRD in making determinations regarding whether wells have the potential to cause substantial interference with surface water supplies and empower OWRD to control such interference.

This paper will describe the overarching design of Division 9. It will then discuss challenges to implementing Division 9 including how OWRD assesses triggers for enforcing groundwater curtailment and what constitutes a "timely and effective" impact. It will further explore tools available to water users such as using reduced pump rates and emergency drought declaration pumping options and how these tools interact with Division 9 rules. Lastly, it will describe the effectiveness and impact of these rules in areas particularly affected by drought.

INTRODUCTION

The Oregon groundwater code was adopted under the prior appropriation doctrine, following the maxim of "first in time, first in right." This body of law was developed far before there was a modern understanding of hydrologic connection between ground and surface water. Thus, ground and surface water are treated as distinct entities under

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Oregon law despite the currently acknowledged interconnected nature of the resources in certain areas.

In order to accommodate the growing need for regulation between surface and groundwater interaction, OWRD has implemented administrative rules that govern groundwater interference with surface water to facilitate administration of water during times of scarcity. These rules have had varying success as many of the statutorily defined triggers are arbitrary thresholds and not scientifically based.

DIVISION 9 ADMINISTRATIVE RULES

Authorized by Oregon Revised Statutes 537.505 to 537.795, Division 9 of the Oregon Administrative Rules regulates groundwater interference with surface water. These rules require that the Water Resources Commission administer the appropriation and use of groundwater resources in the State of Oregon.[2] Specifically, the rules determine where groundwater is hydraulically connected to, and the use interferes with, surface water.[3]

The stated policy of rules is to establish criteria to guide OWRD's determination as to whether wells have the potential to cause substantial interference with surface water supplies and direct how OWRD should control that interference.[4] The rules apply to all wells, and to all existing and proposed appropriations of groundwater except exempt uses.[5] Importantly, these rules allow for local rules to supersede them in certain circumstances, such as in the Klamath Basin Adjudication.[6]

In order to determine if there is a hydraulic connection and potential for substantial interference OWRD must first determine whether wells produce water from a confined or unconfined aquifer using the water well report or best available information.[7] If a well is within a ¼ mile of a surface water source, it is <u>assumed</u> the well will be hydrologically connected to the surface water unless the applicant can prove otherwise.[8]

Once a well is determined to be hydrologically connected to a surface water source, the well is <u>presumed</u> to have a substantial interference with the surface water if:

-the well is within a horizontal ¼ mile of the surface water;

-the rate is greater than 5 cfs;

-if the Point of Appropriation ("POA") is less than one mile from the surface water source;

[2] O.A. R. 690-009-0010 (2013).
[3] *Id.*
[4] O.A. R. 690-009-0030 (2013).
[5] *Id.*
[6] *Id.*
[7] O.A. R. 690-009-0040(1) (2013).
[8] O.A. R. 690-009-0040(2) (2013).

-if the POA is within one horizontal mile from the surface water source and the rate of appropriation is greater than one percent of minimum streamflow or instream water right with senior priority;

-the discharge that is equaled or exceeded 80 percent of the time; or

the appropriation, if continued for 30 days, and is within one mile horizontally from the surface water, would result in stream depletion greater than 25 percent of the rate of appropriation.[9]

If OWRD wishes to control the use of any well greater than 500 feet from a surface water source, it must determine if that control would provide relief in an effective and timely manner using methods laid out in OAR 690-009-0040(4)(d).[10] Lastly, if OWRD wants to control a well greater than one mile from a surface water source, it must do it through a critical groundwater area determination, as outlined in ORS 537.730 to 537.740.[11]

CHALLENGES OF REGULATING GROUNDWATER AND SURFACE WATER CONNECTIVITY

Recent conflicts surrounding groundwater regulation due to surface water connectivity have been focused in the Klamath Basin. In this area, groundwater users have been regulated based upon the assumption and presumptions established by Division 9 rules. These regulations have been on wells greater than 500 feet from a surface water source. Because of the well location, OWRD was required to determine if the control would provide relief in an effective and timely manner to the impacted surface water source.

This “effectively and timely” determination must be made using the best available information utilizing either (a) suitable equations and graphical techniques described in publications such as Techniques of Water-Resources Investigations of the United States Geological Survey: Book 4, Chapter D1 or (b) a computer program or groundwater model that is based on similar equations or techniques.[12] However, because the technical expertise required to make these determinations lies exclusively with the State, a tremendous burden is placed on the water user being regulated to demonstrate that their water source is not hydrologically connected.

In some areas, groundwater users have been allowed to pump at lesser rates and therefore avoid a “timely and effective” finding. It is unclear how OWRD has decided upon these rates, unless the rates required are below the rates listed in 690-009-0040 as triggers for determining hydraulic connection and potential for substantial interference. As such, OWRD is shutting off some users’ altogether, while at the same time indicating there is a “safe” level to continue pumping. This incongruity among rate of pumping and water connectivity continues to create confusion and frustration among users that are attempting to plan for water needs for upcoming growing seasons.

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[9] O.A. R. 690-009-0040(4) (2013).
[10] O.A. R. 690-009-0050(2)(a) (2013).
[11] O.A. R. 690-009-0050(2)(b) (2013).
[12] O.A. R. 690-009-0040(4)(d) (2013).

DROUGHT TOOLS

In addition to regulating surface and groundwater together, Oregon has also developed a suite of drought mitigation tools in order to mitigate problems that may develop when water supplies are inadequate. These tools are provided for by Division 19 of the Oregon Administrative Rules, and are authorized by ORS 536.700 through 536.780 as Emergency Water Shortage Powers.[13] Importantly, the rules become operative only during extraordinary drought situations.[14]

During a drought declaration, these administrative rules allow the Commission or the Director of the Water Resources Department to allow emergency water use under the terms of emergency use permits; waive notice and reporting requirements pertaining to water well construction; allow temporary exchanges of water as allowed under ORS 540.533 without requiring notice; grant preferences for human consumption and stock watering; or allow for a temporary change in use, place of use or point of diversion under the terms of an emergency use permit without complying with the notice and waiting requirements under ORS 540.520.[15] Although a drought declaration must be in place, these tools provide for several innovative solutions for water users that are facing shortages.

Importantly, emergency permits available in Division 19 require a finding of “no injury” before they can be implemented. Additionally, the emergency permit cannot impair or be detrimental to the public interest. In making the assessment, the Director must consider the factors outlined in OAR 690-310-0120 and 690-310-0130, the need for water, and the short term nature of the proposed emergency.[16] Other tools, such as temporary drought transfers and drought instream leases also require findings that no injury to water users will occur.[17] However, due to the lack of information surrounding groundwater and surface water interaction, long term impacts of emergency use is largely unknown at this time.

Nevertheless, drought transfers and temporary substitution of supplemental groundwater rights for surface water primary rights provide opportunities for individual water users to maintain some water use in the face of drought by engaging in a water market. Through this process, individuals can assess what their most productive needs are and triage what areas or crops should receive water over others. This allows for movement of water rights such that the water use can be utilized to maximize productivity without concern about using water on a place of use where it is not authorized. Thus, it provides an important tool for farmers and ranchers attempting to maintain their livelihood in the face of ongoing drought.

[13] O.A. R. 690-019-0010 (2013).
[14] *Id*.
[15] O.A. R. 690-019-0030 (2013).
[16] O.A. R. 690-019-0040 (2013).
[17] O.A. R. 690-019-0055; 690-019-0058 (2013).

CONCLUSION

Governing groundwater and surface water connectivity is a challenge. The resource is complex and the rules and enforcement of rules are ever changing. Thus, water users, attorneys and other water professionals must remain vigilant to change and voice concerns regarding how regulation impacts water use rights. While rules have been implemented to guide administration of water use during times of shortage, the difficulty of implementing the regulations to such an unknown resource has proven difficult.

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WATER CONSERVATION IN WESTERN NEVADA COUNTY, CALIFORNIA

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ABSTRACT

In 2015 California was in the fourth year of below average precipitation. On May 5, 2015 the California State Water Resources Control Board (SWRCB) enacted drought restrictions designed to help Californians reduce their water use by 25 percent statewide. The Nevada Irrigation District (NID) was identified by the SWRCB as being in the highest tier of residential water use in the summer of 2014. To comply with the SWRCB regulations and to preserve some carryover storage, residential water users were asked to reduce water usage by 36 percent compared to water usage in 2013. The Cities of Grass Valley and Nevada City and the Washington County Water District (WCWD) were required to reduce water use by 25 percent compared to 2013.

This paper will describe the efforts of NID and the cities of Grass Valley and Nevada City and the WCWD to reduce residential water use in 2015 and the results of those efforts. Also described will be water conservation efforts and results for NID's agricultural water customers who were asked to voluntarily reduce their water use for the year. An update will also be provided on the State funded water supply and conservation implementation projects for the City of Nevada City and the WCWD.

INTRODUCTION

In 2015 California was in the fourth year of below average precipitation. On May 5, 2015 the California State Water Resources Control Board (SWRCB) enacted drought restrictions designed to help Californians reduce their water use by 25 percent statewide. The Nevada Irrigation District (NID) service area was identified by the SWRCB as being in the highest tier of urban water use in the summer of 2014, over 214 gallons per capita per day (GPCD). To comply with the SWRCB regulations, NID was required to reduce water usage by 36 percent compared to water usage in 2013. The SWRCB defines an "Urban Water Supplier" as a private or public entity that supplies water to more than 3,000 customers or supplies more than 3,000 acre-feet (AF) annually. Since the Cites of Grass Valley and Nevada City and the WCWD supply less than 3,000 AF per year, they were required to reduce potable water production by 25 percent compared to 2013.

Western Nevada County is located in Northeastern California approximately 50 to 70 miles northeast of Sacramento (Figure 1).

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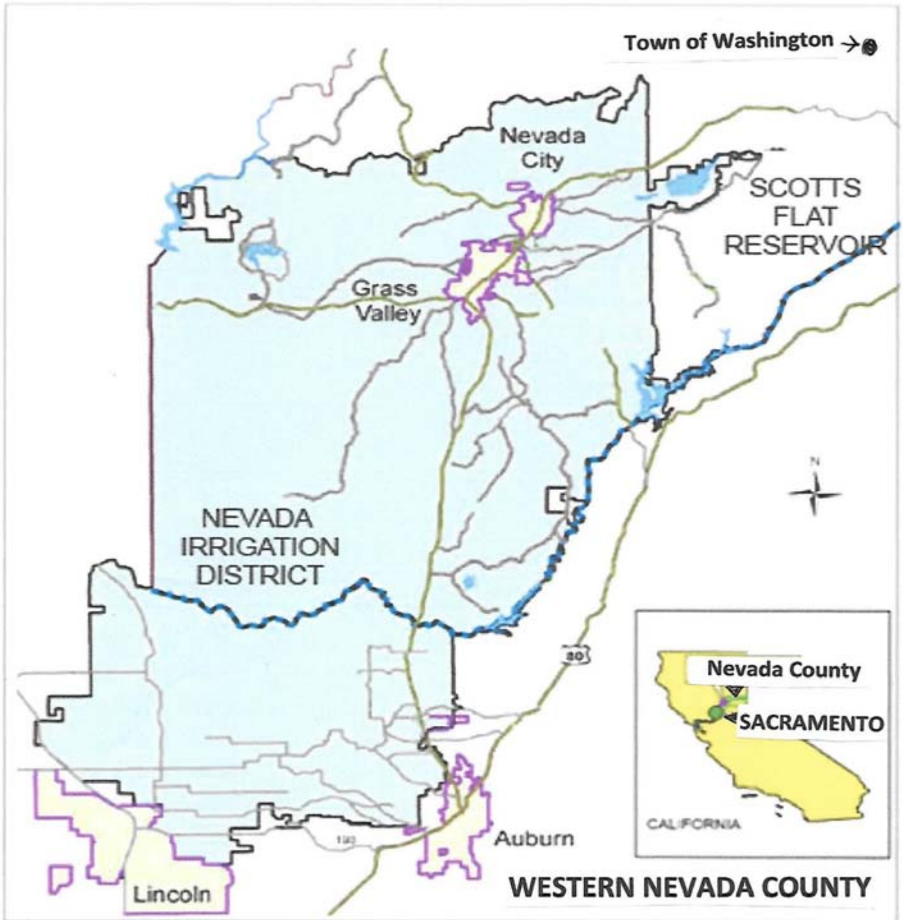

Figure 1. Western Nevada County

The water drought in California began in water year 2011-2012 (October to September) after a very wet water year 2010-2011 (Table 1). Precipitation at the Nevada City Water Treatment Plant continued to be above average in 2010 – 2011 and 2011-2012 (precipitation year July to June) and then dropped off for the next three years. The 2015-2016 precipitation year is off to a good start, with precipitation through March 31, 2016 being 125% of the long term average (Table 2).

Table 1. Yuba River Near Smartsville

WATER YEAR - OCTOBER TO SEPTEMBER	FLOW IN 1,000 ACRE-FEET	PERCENTAGE OF AVERAGE ANNUAL FLOW
1951 to 2000 Average	2,459	100
2010 – 2011	3,855	157
2011 - 2012	1,543	63
2012 - 2013	1,494	61
2013 - 2014	881	36
2014 - 2015	877	36

Table 2. Precipitation at Nevada City Water Treatment Plant

PRECIPITATION YEAR JULY TO JUNE	PRECIPITATION IN INCHES	PERCENTAGE OF ANNUAL AVERAGE
Long Term Average	53.38	100
2010 - 2011	87.49	164
2011 -2012	79.68	149
2012 - 2013	53.31	100
2013 -2014	39.42	74
2014 - 2015	38.42	72
2015-2016 Through 3-31-2016	58.93	125% Through 3-31-2016

NEVADA IRRIGATION DISTRICT

Nevada Irrigation District (NID), an independent special district within the State of California, was established in 1921 by a vote of the residents of Nevada County, California. At its formation it encompassed 202,000 acres. In 1926 NID was expanded to include 66,500 acres in western Placer County. During the 1920's NID obtained water rights and land to store and deliver water. In 1966 NID began hydroelectric production with the completion of the Yuba-Bear Power Project.

Today NID encompasses a total of 287,000 acres. It supplies residential, municipal, commercial, industrial, and agricultural water, produces electricity, and public recreational areas. NID has ten reservoirs on the western slope of the Sierra-Nevada Mountains with a total storage capacity of over 280,000 acre-feet. Water is conveyed to the service areas in 400 miles of canals and 300 miles of pipeline.

Water is treated at eight water treatment plants with a combined capacity of over 33 million gallons per day (mgd). Typically about 9,000 AF are supplied to over 18,000 municipal customers each year.

Agricultural water is supplied to almost 5,900 customers who irrigate almost 26,000 acres. About 106,000 AF are supplied in a typical year. Over 18,000 acres of irrigated pasture is by far the major crop, followed by family gardens (4,100 acres) and golf courses and parks (1,000 acres). Wine grapes are a rapidly expanding crop. Other crops include hay, alfalfa, nurseries, apples, pears, peaches, and corn.

NID asked treated water customers to cut use by 36 percent and irrigation customers to reduce water use be at least 25 percent. Outreach included a public meeting on water conservation in May 2015, articles in NID's Newsletter "Waterways" which is included with water bills, and a tabulation of year 2013 water use sent to customers so they could track their reduced water use in 2015. Urban water use was reduce by 36 percent during the summer months of 2015 compared to 2013; however savings were reduced to about 20 percent in September and October. The overall reduction for 2015 was about 31 percent compared to 2013.

NID distributed a fact sheet on conservation tips for agricultural operations to irrigation customers. These customers were asked to voluntarily reduce their water use by 25 percent for 2015, with the assurance that they could get their full allotment in future years. Irrigation and spill reductions for 2015 were about 16 percent compared to 2013.

The 2015-2016 water year is off to a good start for NID. As of March 31, 2016, the snowpack in NID's reservoirs watershed is 102% of normal for that date. The overall storage in NID's reservoirs for that date was 93% of capacity and 135% of the long term average. The current SWRCB conservation target for NID has been reduced from 36% to 33% water savings for 2016 compared to 2013 water use. NID is joining other water suppliers in Northern California in requesting the SWRCB to further relax water conservation requirements.

CITY OF GRASS VALLEY

The City of Grass Valley is located approximately 57 miles northeast of Sacramento, on State Routes 49. With a population of about 13,000, the city is surrounded by forests and is roughly at 2,500 feet elevation. NID supplies treated water to about 7,400 people, and supplies about 1,200 AF of raw water to the City, which treats the water and supplies it to the remaining 5,600 people.

Water savings compared to 2013 for the high water use months of June through November averaged 28.6 percent, with a reduction from about 243 million gallons (240 GPCD) to about 173 million gallons (170 GPCD). This exceeded the required reduction of 25 percent for entities supplying less than 3,000 AF per year.

The city's water conservation in 2015 has been attributed to their outreach campaign requesting customers to conserve, their enforcement campaign to educate people on the City's requirements, and the adoption of mandatory water conservation requirements which severely limited urban irrigation, and repair of water mains and leaking water services. The City also used portable changeable message signs which encouraged the residents to save water.

CITY OF NEVADA CITY

The City of Nevada City is located approximately 60 miles northeast of Sacramento, at the junction of State Routes 49 and 20. With a population of about 3,000, the city is surrounded by heavily forested lands and is roughly 2,500 feet in elevation. The historic downtown and recreational opportunities in the area have made the City an important tourist destination. As the Nevada County seat, it is also home to governmental offices, as well as the headquarters for the Tahoe National Forest. The daily population increases by 50 to 70 percent as a result of this workforce and also increases regularly on weekends, holidays and over the summer months with considerable influxes of tourists. The city covers approximately two square miles, of which 60 percent is served with treated water. There are approximately 1,350 water customers located within the city limits. While segments of the water supply system have been replaced over time, much of the downtown is served by pipes and mains that date from the 1860's and 1870's. Water is diverted from Little Deer Creek which typical flows from October or November through May or June to a reservoir with an active capacity of about 54 AF. Once the water demand exceeds the flow of Little Deer Creek and reservoir storage, raw water is purchased from NID and released from a nearby canal. The City then treats and distributes the water.

Water use for calendar years 2005 to 2015 is summarized in Table 3.

Table 3. Water Use in Nevada City, 2005 to 2015.

Calendar Year	Purchase from NID, Acre -Feet	Little Deer Creek, Acre-Feet	Demand, in Acre-Feet	Demand in Million Gallons	Per Capita Use, Gallons per Day (GPCD)
2006	432	557	989	322	294
2007	428	561	931	303	277
2008	578	404	982	320	291
2009	363	484	847	276	252
2010	247	572	819	267	244
2011	185	603	788	257	235
2012	192	572	764	249	227
2013	287	446	733	239	218
2014	299	360	659	214	195
2015	224	282	506	165	151

For the 10 year period there has been a general trend of less water use. Prior to the drought, this can be attributed to adjusting the tiered water rate structure and better management of water deliveries to reduce spills at the City's water storage tanks. The City now has four cross trained and qualified employees who manage and staff both the water treatment and wastewater treatment plants.

As the drought became more severe in 2014 and 2015, the City adopted two resolutions requiring mandatory water restrictions including limiting outdoor water use to two days per week. The 2015 resolution also required all customers to reduce potable water use by 25 percent and encouraged them to reduce use by 35 percent for the months of July 2015 through February 2016 as compared to the amount used for the same months in 2013. The City has begun using reclaimed wastewater for all the processes at their wastewater treatment plant which saved over 1.3 million gallons (about 4.2 AF) per month during the summer of 2015. The City also developed a Drought Action Plan which included a water shortage contingence strategy to be implemented in future years of water shortage.

2015 water use was almost 31 percent less than 2013 water use; 218 GPCD in 2013 and 151 GPCD in 2015. This exceeded the required reduction of 25 percent for entities supplying less than 3,000 AF per year.

In November 2006, California voters passed Proposition 84, the Safe Drinking Water, Water Quality, and Supply, Flood Control, River and Coastal Protection Bond Act. With funding provided by the act the City is currently upgrading the control and monitoring system at the water treatment plant, replacing and adding new water distribution pipelines, installing altitude valves at the three water storage tanks, and installing a SCADA system to monitor and control the storage levels in the tanks.

WASHINGTON COUNTY WATER DISTRICT

The Town of Washington is an unincorporated community located in Western Nevada County, approximately 13 miles east of Nevada City, on the South Fork of the Yuba River. The community is small and isolated, with few opportunities for expansion due to wild and rugged watershed lands and additionally surrounded entirely by Tahoe National Forest property.

The Washington County Water District (WCWD) is the only water agency serving the community. The district provides water through 122 hook-ups that serve approximately 140 residents and businesses, including two campgrounds and a hotel with a bar and restaurant. Washington is also a popular recreation destination, which results in considerable spikes in summertime water use. While wintertime water use is about 144,000 gallons per day, it doubles to 288,000 gallons per day in the summer.

The infrastructure that serves the district is aging and was installed prior to development of modern conservation standards. In 2015 using Proposition 84 funding, WCWD installed water meters for all customers, made repairs to its water conveyance and distribution system, and replaced fire hydrants with freeze proof models. Many of the old hydrants were dripping water to prevent freezing in the winter. Due to this work, water deliveries in 2015 were reduced by 38% compared to 2013. This exceeded the required reduction of 25 percent for entities supplying less than 3,000 AF per year. Outreach to customers by the WCWD included mailing inserts with water bills and posting of water conservation messages on public bulletin boards.

Additional Proposition 84 funding will be used in the next two years to make improvements to their water treatment plant, replace failing parts of their main water conveyance pipeline, install an altitude valve at their water storage tank, and add pumps to provide a minimum of 20 pounds per square inch of pressure for all customers.

CONCLUSION

In response to the four-year drought, entities and customers in Western Nevada County were able to reduce water use by 25 to 38 percent for 2015 compared to 2013. This compares well with urban water savings throughout Northern California being about 24% for the same period. The 36 percent state mandate for urban water suppliers, including NID, who delivered over 214 GPCD in the summer of 2013 was probably unrealistic, but other water suppliers in Western Nevada County met the State mandated goals. With precipitation returning to near normal levels in 2016, some relaxing of conservation goals by the SWRCB has taken place.

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MANAGING FOR DEFICIT IRRIGATION

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ABSTRACT

This paper deals with budgeting of irrigation water for deficit irrigation – deciding how much water to use for a season and how much to allocate to each stage of crop development. When irrigation water is applied as needed to meet crop water demands (i.e. full irrigation) the amount of water to be used is determined by the crop itself, and irrigation timing is commonly based on real time observations of field conditions. But when a crop is deliberately under-irrigated the amounts and timing of water use need to be decided in advance.

The central theme of this paper is that success in deficit irrigation management will depend more on advanced and sophisticated modeling, and less on real time monitoring technologies.

Making the best use of limited water requires sophisticated modeling to assess alternative water use strategies, plan the allocations of water through the season to implement a preferred strategy, and adapt the implementation plan to accommodate the specific circumstances of individual fields. Modeling also provides a scientific basis for interpreting feedback data from the field as the season evolves. All of this involves substantial variability and uncertainty. It is a modeling challenge.

An advanced decision support system developed explicitly for deficit irrigation management addresses these challenges. Distinguishing features include:

(1) sophisticated modeling of the disposition of applied water enables derivation of field-specific crop production functions and long-range projection of crop water availability
(2) anticipated irrigation schedules can be routinely and continuously updated to accommodate unexpected circumstances or changing constraints
(3) adaptive feedback can be used to increase analytical precision, minimize uncertainty and provide insight into field-specific relationships between water use and crop production

The characteristics and performance of this decision support system will be outlined and the utility of the information it provides will be illustrated by two case studies, one involving optimum irrigation with high pumping energy costs, the other concerning deficit irrigation of an almond orchard under severe drought conditions.

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INTRODUCTION

Systematic, science based procedures for irrigation management appeared about five decades ago with the advent of *scientific irrigation scheduling* (SIS). The prevailing management paradigm of the time was *full irrigation*; the objective was to maximize crop yields while minimizing water losses. But in recent years there has been increasing interest in partial irrigation, or *deficit irrigation*, an altogether different and more challenging management paradigm (English, et al. 2002). That increasing interest is reflected in the appearance of technical bulletins on the subject from diverse institutions worldwide (e.g. FAO, 2002; UCANR, 2016).

The objective of deficit irrigation is to maximize net economic returns rather than maximizing yields *per se*. The focus on economic returns is increasingly motivated by competition for water. Farm water supplies are often simply insufficient for full irrigation, as forcefully demonstrated recently in the devastating California drought. But even when a farm has access to ample water, partial irrigation can be more profitable, especially when competing demands for water create opportunity costs for water. The forces driving this competition -- food shortages, energy costs and global water shortages -- will only grow stronger in the next few decades (English, 2010).

Deficit irrigation, the natural response to those forces, requires a fundamental change in the way irrigation is managed. Conventional, full-irrigation management has commonly relied on continuous monitoring of soil water depletion or crop stress to determine when to irrigate and how much to apply. We would characterize that approach as '*real time scheduling'*. And, significantly, with conventional SIS the total amount of water to be used for the season *is not a management decision*, it is determined by crop water demand.

Deficit irrigation management is altogether different and more complicated. The manager must decide *in advance* how much water to use for the season, when to use that water and *when to withhold it*. That requires analyzing how a sequence of irrigations will play out months into the future. For purposes of this discussion we will refer to such long range projections of irrigation schedules as 'forward scheduling'.

The central theme of this paper is that success in deficit irrigation management depends less on real time scheduling technologies and more on advanced and sophisticated modeling for forward scheduling.

Optimal management of deficit irrigation requires: (i) evaluating expected outcomes for alternative management strategies; (ii) testing the feasibility of preferred strategies (iii) translating preferred strategies into detailed, full season irrigation plans; (iv) customizing those plans to accommodate the unique circumstances and constraints of specific fields; (v) tracking implementation of scheduling plans to assure adherence to the overall strategy; and (vi) updating plans as conditions evolve during the season. These capabilities will be illustrated in the present paper.

Advanced technical support is needed for dealing with these analytical challenges, and incremental improvements in current technologies will not meet that need. While current management technologies largely rely on instrumentation to monitor field conditions in real time, deficit irrigation management will require sophisticated modeling -- in future time -- of the whole complex system; irrigation hardware performance; management preferences; operational constraints; the disposition of applied water in heterogeneous fields; and the physiological responses of the crop.

Recognizing the need for a new generation of management modeling, the USDA and other agencies funded development of a practical decision support system for deficit irrigation[3] known as *Irrigation Management Online* (IMO) (Hillyer and Sayde; 2010). This paper reviews the experience and general insights gained from beta testing of IMO for two cases; irrigation with high cost energy in the Columbia Basin, and management of a severely limited water supply for almonds in the California drought.

A DECISION SUPPORT SYSTEM

Development of IMO was based on three key design objectives. The first design objective was that the system should *embrace analytical complexity*. Simple water balance modeling cannot adequately represent the whole complex of dynamic, interacting processes involving soils, climate, crop, water supply, irrigation system and management practices that relate applied water to crop development and yield.

The second design objective was to *streamline the computational process* to facilitate rapid analysis of alternative irrigation strategies. Computationally efficient analytical tools such as linear programming or genetic algorithms have not been capable of dealing with the complexity of deficit irrigation management. Optimization will necessarily involve simulation and iterative search which will entail heavy computational burdens. The analytical software must therefore be designed for maximum speed and efficiency.

The third design objective was to *fully engage the user as a direct participant* in the analytical process. Any seasonal water use plan generated by IMO must align with the objectives, experience and preferences of the farm manager. To account for such subjective factors requires direct input from the client/manager.

These design objectives are reflected in the following key features of the IMO system:

- sophisticated modeling of the disposition and fate of applied water enables more accurate simulation and long-range projections of crop water availability
- modeling of application efficiency coupled with general, ET based yield models can realistically simulate crop response to applied water, an essential capability for optimum management.

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[3] The National Research Initiative Program, Natural Resource Conservation Service and Risk Management Agency of USDA provided approximately $2 million of funding. Additional support was provided by the Bonneville Power Administration, the States of Oregon, Washington and California and the New Zealand Ministry of Agriculture.

- efficient analytical algorithms and advanced software design enable rapid search for optimal strategies and rapid updating of seasonal plans as circumstances change
- an editable calendar enables the farm manager to make short term modifications to irrigation schedules without compromising overall seasonal planning
- record keeping, integrated displays of alternative sources of field data and retrospective analysis of past seasons provide insight into field-specific relationships between water use and crop production, and facilitate system re-calibration for increased analytical precision.

Applications for Deficit Irrigation Management

We will address four analytical tasks to which IMO has been applied for optimum management of limited water:

- Budgeting water; deciding how much water to use for a coming season
- Forward scheduling; planning the seasonal irrigation schedule to make best use of the limited water
- Error detection and recalibration
- Assessment

BUDGETING WATER

Example 1: Deciding How Much Water to Use When Pumping Costs Are High

The question of how much water to use for a given field may be moot if the water supply is strictly limited, but when a farm has ample water this can be a challenging economic question. As a general rule the profit maximizing level of water use will be somewhat less than the yield maximizing level. The optimum amount to use may be based on the experience of individual farm managers. Some research leaders have offered general guidelines on the optimum. For two examples, Keller and Bleisner, 1990; English and Raja, 1996) have suggested that when water supplies are limited or costly the economic optimum point will be on the order of 10% or 20% less than full irrigation.
If water has a significant opportunity cost, the optimal level of irrigation may be considerably less (English and Raja, 1996). In that case a production function relating applied water to crop yield may be needed to evaluate alternative water use strategies.

Given the variability of weather, soils, antecedent moisture, distribution uniformity, root distributions and other factors, it is difficult to predict how much applied water will actually be used by a crop, and what potential yield will be. When combined with other factors, such as crop response to chemical use, weather conditions, disease, pests and so on, the yield that will be produced by a given level of applied water is virtually impossible to predict with certainty.

Nevertheless, estimation of yields is important for optimal management of deficit irrigation. It is our position that the analytical engine at the heart of IMO realistically represents the complex relationship between applied water and crop yield on a field scale. Having been derived from first principles, it is sufficiently accurate and robust to guide management decisions. An example follows.

Developing a Crop Production Function

A general relationship between crop consumptive use of water, ET and yield is illustrated in Figure 1 (Raes and Geerts; 2009). Zones (c) and (d) of this function are the economically rational range of interest for deficit irrigation. Yields will increase more or less linearly in zone c. Then, for some crops, yield response rates will decline near maximum potential ET (zone (d)). Beyond that point, zone (e), yields will generally decline with the adverse consequences of excess water use.

Figure 2 indicates how ET relates to applied water (NEEA, 2013). As indicated, applied water tracks ET fairly closely in the range corresponding to zone (c). As applied water approaches the yield maximizing point, progressively increasing losses from surface accumulation and runoff, percolation and surface evaporation will cause the applied water curve to depart progressively farther from the ET curve.

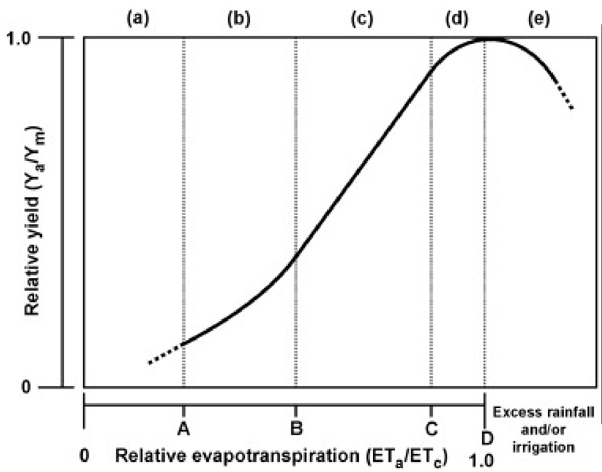


Figure 1. yield response to ET

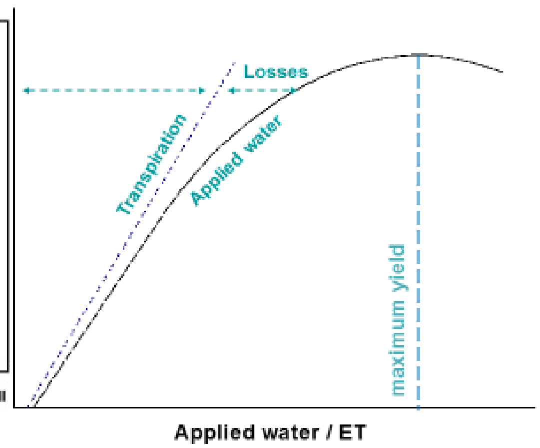


Figure 2. yield response to applied water

IMO estimates yields by modeling these two relationships in tandem. When an increment of water is applied to the field IMO estimates the resulting pattern of incremental ET that across a heterogeneous field. The physiological response of the crop to incremental ET is then used to estimate yields on a field-wide basis.

The IMO system was used for partial irrigation of a circle of alfalfa on a cooperating farm in the Columbia Basin. The analysis considered alternative levels of water use ranging from 50.5 inches (full irrigation) down to 20 inches (67% below full irrigation). The specific management strategies employed for each level of water use were defined in terms of the following five management parameters, each combination of which would result in a specific level of water use:

i) *Irrigation adequacy*, the percentage of the field to be fully irrigated when water is applied

ii) *Management allowed depletion (MAD);* the amount by which soil water content is allowed to be reduced before an irrigation takes place.

iii) *Target refill level*; the target soil moisture level to which the root zone will be refilled during irrigation (expressed as a percentage of available water holding capacity in the root zone)

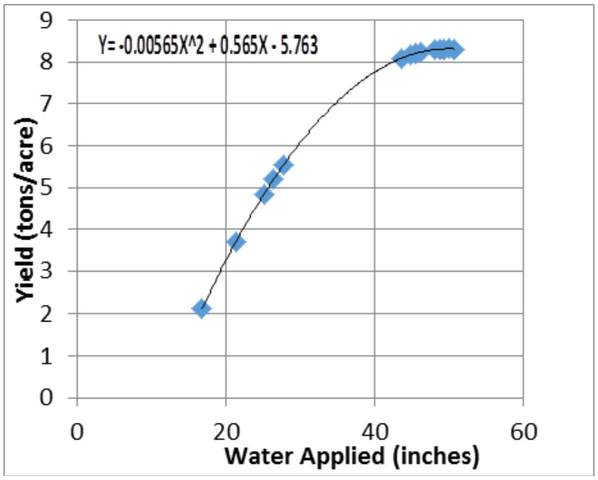
iv) *Assumed application efficiency*; the estimated application efficiency to be used in calculating gross irrigation requirements.

v) *Critical growth stage applications*, the seasonal pattern of applying or withholding irrigations according to stages of growth.

Note: in the case of alfalfa the growth stages are associated with the sequence of cuttings, since yields tend to decline with later cuttings. The discontinuity of data points between 27.7 inches and 43.60 inches of applied water derived from elimination of the last cutting.

Nineteen specific combinations of these parameters were used in this analysis to generate paired values of applied water and yields, as summarized in Table 1. The seventh column shows seasonal water use for each instance. The tenth column shows yields as estimated using the FAO 33 algorithm. (However the yield reduction factor derived by calibrating the FAO 33 algorithm (Doorenbos and Kassam, 1979) with water use and yield data from partial irrigation of six fields on the cooperating farm was 1.17, rather than the FAO published factor of 1.10. The derived production function is shown in Figure 3.

Table 1. Yield response to applied water.



Case	Adqcy	MAD	Refill Target -------	nominal effncy -------	irrigation ending date	Gross applied (inches)	ET	Losses as perc, spray, RO	FAO #33 yields (tons)
1a	87.5	50	100	85	20-Aug	49.9	44.4	6.9	8.99
1b						50.6	44.5	7.4	9.00
1c						50.6	44.5	7.1	9.00
2a	50	50	100	100	20-Aug	49.3	44.3	6.3	8.96
2b						46.1	43.4	5.2	8.91
2c						49.3	44.4	6.3	8.97
4a	nil	50	100	100	20-Aug	48.7	44.2	5.5	8.90
4b						48	44.2	5.3	8.89
4c						48.7	44.2	5.6	8.90
5a	nil	50	80	100	20-Aug	45.5	43.6	4.2	8.80
5b						45.5	43.3	4.3	8.79
5c						44.8	42.9	4.3	8.71
6	nil	60	80	100	20-Aug	43.6	42.2	4.1	8.52
7	nil	70	80	100	20-Aug	42.9	41.2	4	8.00
8	nil	50	80	100	9-Jul	27.7	29.6	2.3	8.08
9	nil	60	80	100	9-Jul	26.4	28.6	2.2	7.83
10	nil	70	80	100	9-Jul	25.1	27.3	2.1	7.32
11	nil	80	80	100	9-Jul	21.3	24.2	1.6	6.35
12	nil	85	60	100	9-Jul	16.8	19.7	1.3	4.66

Figure 3. Crop response function

ALTERNATIVE IRRIGATION STRATEGIES

This function was used to determine optimum water use for a 125 acre field of alfalfa under a center pivot system on a cooperating farm in the central Columbia Basin with high pumping head (300 ft) and energy costs of \$0.09/kwh. Estimated harvest costs were \$42 per ton, and crop sale price \$220 per ton.

We considered three alternative management objectives; first, to maximize yield per acre; second, to maximize net income per acre; third, to maximize net economic returns to water. Since this farm has more land than water, the water saved by deficit irrigation could be used to increase irrigated acreage, with opportunity costs corresponding to net returns to irrigation. The results are indicated in table 2, below. Net income at full irrigation would be \$143,000. If water and energy use is reduced net income would be increased until water use goes below 42.9 inches.

If water use is reduced below 42.9 inches the net income from the single 125 acre circle would be less than that from full irrigation. However if additional income were derived from sale or use of the water conserved, net farm income could continue to increase. In this case we assumed the opportunity cost of water could be captured by irrigating additional land with the same net economic return to water. At the point of maximum net returns to water (27.7 inches) the profit from cropping on the 125 acre pivot would be reduced by $43,148, as indicated. But if the conserved water (22.9 inchesx125 ac = 2863 ac-in) were used to irrigate additional land it would yield an additional profit of (2863 ac-in x $28.93/ac-in = $82,726). Total farm profits would then be increased by (-$43,148 + $82,726 = $39578).

Table 2. Analysis of alternative optimization strategies

Applied water	Crop yield	Revenue	Energy use (kwh/ac)	Energy Cost ($/ac)	Haying costs ($/ac)	Net income ($/acre)	Net for 125 ac	Change in net farm income	net returns to water ($/ac-iin)	(
16.8	2.134	470	1260	113	90	$267	$33,314	-$110,001	15.86	
21.3	3.708	816	1598	144	156	$516	$64,534	-$78,781	24.24	
25.1	4.859	1069	1883	169	204	$695	$86,933	-$56,382	27.71	
26.4	5.215	1147	1980	178	219	$750	$93,763	-$49,553	28.41	
27.7	5.552	1222	2078	187	233	$801	$100,167	-$43,148	28.93	
42.9	8.077	1777	3218	290	339	$1,148	$143,520	$205	26.76	
43.6	8.131	1789	3270	294	341	$1,153	$144,118	$802	26.44	
44.8	8.209	1806	3360	302	345	$1,159	$144,855	$1,540	25.87	
45.5	8.248	1814	3413	307	346	$1,161	$145,118	$1,803	25.52	
45.5	8.248	1814	3413	307	346	$1,161	$145,118	$1,803	25.52	
46.1	8.276	1821	3458	311	348	$1,162	$145,246	$1,930	25.21	
48	8.339	1835	3600	324	350	$1,160	$145,052	$1,736	24.18	
48.7	8.352	1838	3653	329	351	$1,158	$144,751	$1,436	23.78	
48.7	8.352	1838	3653	329	351	$1,158	$144,751	$1,436	23.78	
49.3	8.359	1839	3698	333	351	$1,155	$144,396	$1,081	23.43	
49.3	8.359	1839	3698	333	351	$1,155	$144,396	$1,081	23.43	
49.9	8.362	1840	3743	337	351	$1,152	$143,950	$635	23.08	
50.6	8.360	1839	3795	342	351	$1,147	$143,315	$0	22.66	

- maximize yield per acre
- maximize profit per acre
- maximize profit per acre-ft

FORWARD SCHEDULING

Example 2: Planning a Deficit Irrigation Schedule for Almonds

The second example involves an almond grower in the San Joaquin Valley of California whose available water supply in the fourth year of the recent drought was limited to 250 ac ft for 93.5 acres, or 32 inches, about 60% of full irrigation.

Identifying a Research-Based Strategy

The first step was to review the past practices and experience gained by the producer herself, and to consult with research and extension professionals about recommended general strategies for deficit irrigation.

One primary resource used is shown in Figure 4, from a bulletin prepared by Doll and Shackel (2015) outlining the effect of water stress at various stages of almond development. This provided a general guide to how water should be allocated during the season. A key observation from that bulleting is that deficits can be most easily tolerated during June, the period approaching hull split.

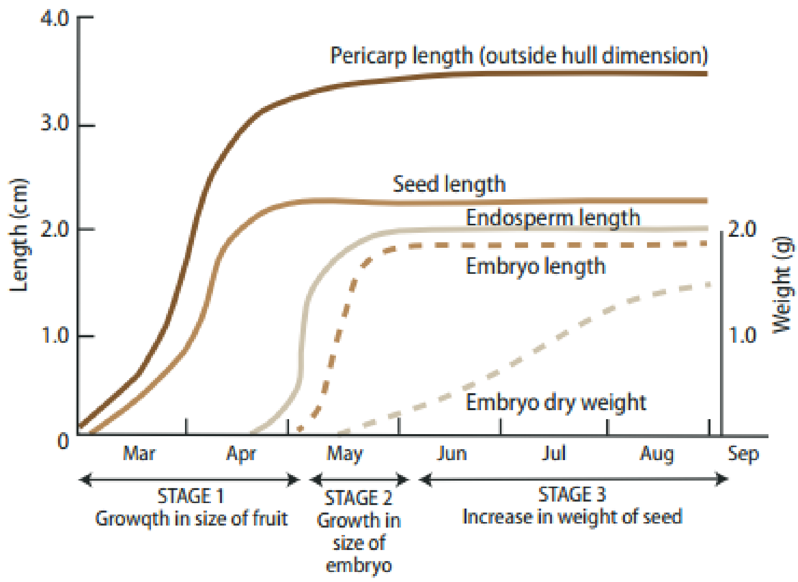


Figure 4. Almond sensitivity to water stress at various stages of development

A second primary source of advice was recommendations for various levels of partial irrigation of almonds, expressed as percentages of PET (PPET) (Goldhammer, IN FAO 66, Steduto, et al., 2012) for each of five phases of crop development. The specific recommendations when available water is 63% of full irrigation, comparable to the cooperating farm situation, are summarized in Table 3.

Table 3: Recommended percentages of PET to be applied when the seasonal water supply is 63% of full irrigation

Phase 1: 70% of PET	the first two months or so following bloom; March and April
Phase 2: 50% of PET	shell hardening, kernel expansion; fruit maturity; May – early June
Phase 3: 25% of PET (later changed to 50%):	hull split, late June
Phase 4: 100% of PET	approaching harvest
Phase 5: 60% of PET	post-harvest

This schedule indicates a tolerance for more stress in June, which is consistent with Doll’s graph. It also advises more water use in July, approaching harvest.

A third key source, Ken Shackel at UC Davis, advised a generally uniform pattern of stress through the entire season, with the exception of increased stress approaching hull split.

The final strategy was a version of the pattern in Table 3, with two modifications: the first was to allocate less irrigation water to Phase 1, relying on antecedent moisture for a significant fraction of crop water use. The second was to increase water use in Phase 3 to 50% of potential PET.

The strategy thus derived then needed to be translated into specified irrigation dates and set times. The challenge was to allocate 32 inches of water over a seven month season, according to the water use pattern stipulated in Table 1, to maximize crop production, ensure good crop quality and minimize detrimental effects on the following season's crop.

Allocations According to Stages of Development

IMO was used to downloaded all historical weather data from the California Irrigation Management Information System (CIMIS) Los Banos station and compile a day-by-day profile of average reference ET. These were converted to crop potential ET and Monthly allocations of water were calculated according to the prescribed values in Table 1. The bar chart in Figure 5 shows crop potential ET (blue) and recommended allocations (yellow) for each of the five prescribed stages of crop development.

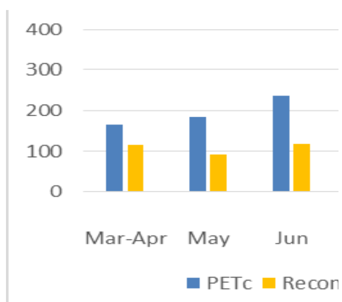


Figure 5. Potential ET and recommended allocations of water

Forward Scheduling

A detailed irrigation schedule was generated using IMO in an iterative search. A preliminary schedule was first generated automatically by IMO to use the 32 inches of available water in a pattern approximating that shown in Figure 5. Successive iterations in a guided search by an analyst until a sequence was found that would adapt the schedule to the specific circumstances of the farm to ensure that it was feasible, practical and consistent with irrigation system capabilities, constraints and normal farm practices. The resulting schedule is shown in Table 4. A season-long projection of crop available water in a five foot root zone is shown in the accompanying graph (Figure 6). The black data points in upper left are neutron probe measurements to determine antecedent moisture. The red bars represent dates and amounts of irrigation events.

Table 4. Suggested irrigation dates and set times

Start Date	Gross Application(inches)	Set/Block/Rotation (hours)
3/24/2015 6:00 AM	0.72	12.0
4/8/2015 6:00 AM	1.44	24.0
4/22/2015 6:00 AM	1.44	24.0
5/5/2015 6:00 AM	1.44	24.0
5/11/2015 6:00 AM	1.44	24.0
5/20/2015 6:00 AM	1.44	24.0
6/2/2015 6:00 AM	1.44	24.0
6/8/2015 6:00 AM	1.44	24.0
6/17/2015 6:00 AM	1.44	24.0
6/22/2015 6:00 AM	1.44	24.0
7/1/2015 6:00 AM	1.44	24.0
7/6/2015 6:00 AM	1.44	24.0
7/13/2015 6:00 AM	1.44	24.0
7/20/2015 6:00 AM	1.44	24.0
7/28/2015 6:00 AM	1.44	24.0
8/5/2015 6:00 AM	1.44	24.0
8/11/2015 6:00 AM	1.44	24.0
8/24/2015 6:00 AM	1.44	24.0
9/2/2015 6:00 AM	1.44	24.0
9/16/2015 6:00 AM	1.44	24.0
9/29/2015 6:00 AM	1.44	24.0

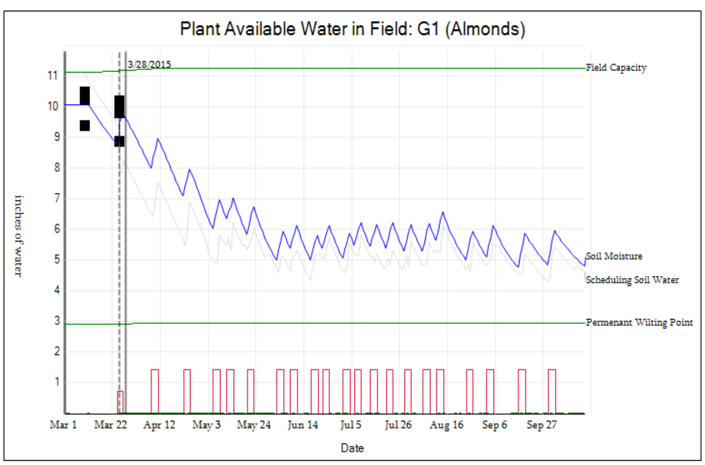


Figure 6. Anticipated seasonal pattern of crop water availability

<u>Tracking and Updating the Plan</u>

As the season evolved IMO was used to track water use and field conditions and revise the schedule as needed to ensure adherence to the intended management strategy. The plan was revised during the season to account for weather anomalies and changing forecasts of available water. Figure 7 shows historical daily average PET as derived from the CIMIS station at Los Banos (plotted in red) and specific 2015 daily values (plotted in blue). The 2015 data departed substantially from expected values in May and July. The reduced ET was also compounded by unexpectedly high rainfall early in May. Additionally, the available water supply was increased slightly during the season. Consequently, some of the water originally allotted for May was shifted to July.

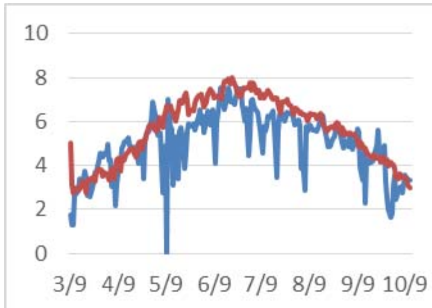


Figure 7. Estimated daily potential ET and observed daily PET

ERROR DETECTION AND RECALIBRATION

Error Detection

The long range projections of crop water availability are subject to several sources of error. One factor, antecedent moisture, can often be a significant fraction of a water budget, but how much antecedent moisture will contribute to crop water use over the course of the season can be difficult to predict. Other important uncertain factors are estimates of the *potential* crop ET, upon which the plan is based, particularly due to the variability of k_c, the crop coefficient. Another parameter, K_s, which accounts for the reduction of actual ET when the crop is water-stressed is intrinsically uncertain, and algorithms for estimating K_s are generally linked to soil water holding capacity, which is itself uncertain.

Given these and other elements of uncertainty, deficit irrigation management should include error trapping and recalibrating of the analytical engine as routine operations. The detailed and integrated records of water use, soil moisture conditions and weather produced by IMO, combined with observations of crop development, crop stress and yield, provides an opportunity for systematically processing a mass of potentially valuable information from which a manager can gain insight and refined understanding of optimal water management.

IMO provides two ways to deal with these issues. One is by tracking soil moisture conditions to detect errors in long range projections of actual crop ET. The other is by integrating feedback data from alternative, independent sources. These are illustrated below.

Tracking Soil Moisture

In the case of the almond producer, it was clear early in the season that pre-season projections of crop available water were significantly lower than indicated by neutron probe measurements, and the error became progressively greater with time. Figure 8 illustrates the cumulative error by mid-May. The error was initially traced to two sources; the crop coefficients for early season ET were too high, and the estimated emitter discharge rate was about 6% low. The crop coefficients were revised in mid-season based on research done separately by Sandon, Ayars and Goldhammer (Goldhammer; IN FAO 66, Steduto et als, 2012). The emitter discharge rate was revised based on District measurements of water deliveries. Subsequently the assumed effective root zone available soil water holding capacity were adjusted. Figure 9 shows how model estimates (blue) would have compared with neutron probe measurements of soil moisture by the end of the season if not calibrated during the season. Figure 10 illustrates the revised soil moisture plot after recalibration. Such recalibration will be an iterative process, with further refinement of model parameters in succeeding years.

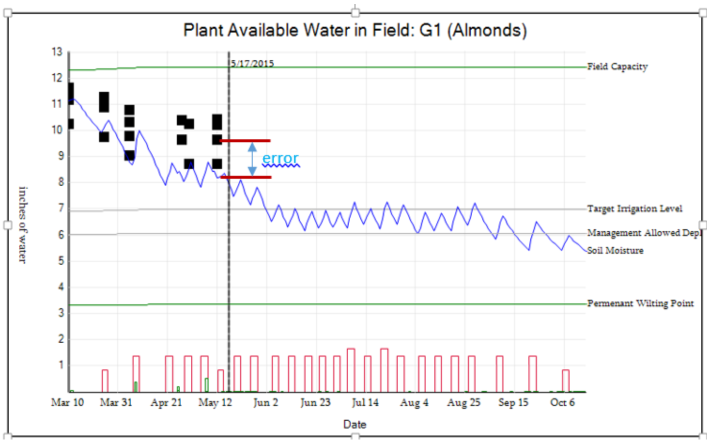


Figure 8. Error in projected soil moisture as of May 17, 2015

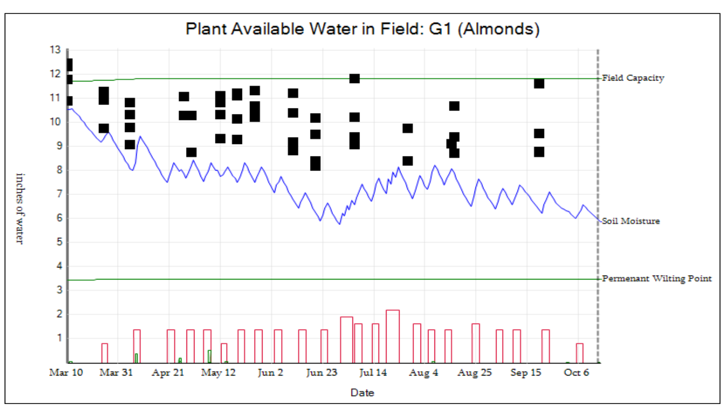


Figure 9. Uncalibrated soil moisture estimates

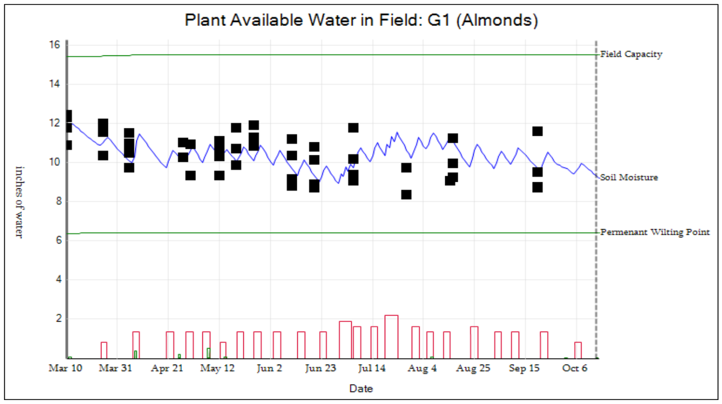


Figure 10. Calibrated projection of season soil moisture

Integrating Alternative Feedback Data

Displaying multiple, independent sources of information about crop water status provides a basis for informed judgement of the quality of each data source. Figure 11 displays three independent data sets in a single graph: soil moisture estimates (derived from ET data), neutron probe readings and, along the bottom of the graph, annotated values of stem water potential.

As an example of the utility of integrated displays, a stem water potential reading of 16.0 in late March indicated incipient stress, indicating that the trees should be irrigated earlier than originally planned. But ET based modeling and neutron probe readings indicated there crop water availability was high. The consistent progression of the soil moisture data was judged to supersede the stem water potential readings and no additional irrigation was called for. (It was later concluded that the SWP readings had not been done correctly.)

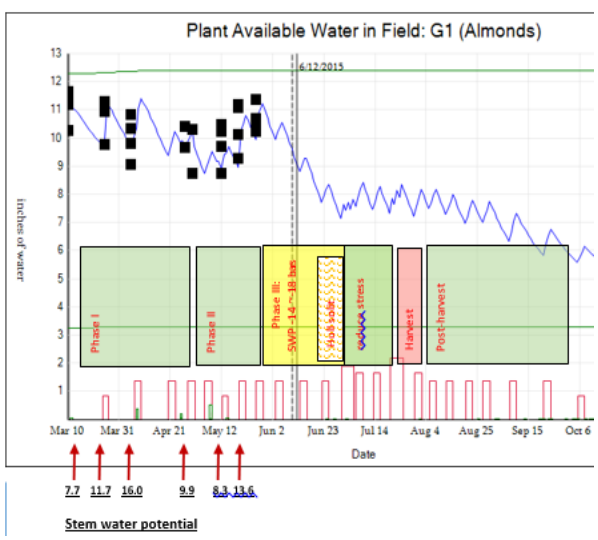


Figure 11. Comparing ET based estimates, neutron probe readings and stem water potential with the original projection of season soil moisture with neutron probe data

While this example involves subjective use of independent data, we have also experimented with a more systematic procedure for combining alternative types of information using Bayesian Decision Theory (English and Sayde, 2008).

ASSESSMENT

It is not possible to quantify the benefits of this decision support system in terms of improved crop production, since there was no 'control' field. Nevertheless we can take note of the farm manager's subjective assessment of the system. Additionally we can describe in detail how well the actual irrigation schedule conformed to the advice of the research and extension community.

The Manager's Perspective

The value of the forward scheduling with IMO, expressed subjectively by the farm manager, was that it 'takes the guesswork out of it". Early in the season she was concerned that neighbors had begun irrigating and she wondered if she should also. With the seasonal plan in place she delayed starting for about two weeks, which enabled one additional irrigation at a more propitious time later in the season. As the season went on the question of whether to irrigate or delay recurred continuously. Ultimately she was comfortable following the plan precisely for the entire season, with the exception of shifting a day or two on one or two occasions because of conflicts with other activities.

Another important advantage from her perspective was knowing when to order district water.

Conformity with Research Guidelines

A second question was whether the pattern of water use was aligned with the research-based guidelines from which the irrigation strategy was originally derived. Figure 12 compares the recommended pattern of allocations (blue), the applied irrigation water (red) and the net crop water use (irrigation plus net change in soil water content at each stage, providing a visual indication of how well the pattern of actual allocations tracked the recommended pattern. Total water use for the season was 248 ac ft, almost exactly the original allotment of 250 ac ft.

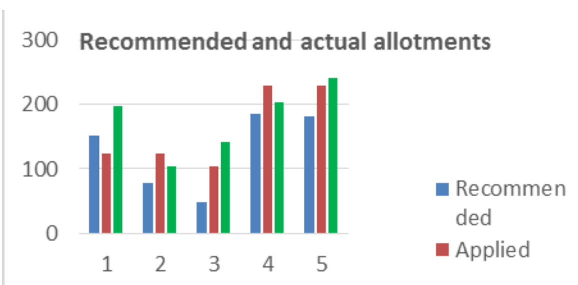


Figure 12: Actual patterns of crop water availability (green) and recommended pattern (blue)

Figure 13 shows a stress index (calculated ratio of actual ET to potential ET) plotted in parallel with Doll and Shackel's graphic of stress sensitivity, providing a general indication of the effectiveness of the stress management strategy. The stress pattern indicates that there was ample water until late May, then increasing stress approaching hull split, and quick recovery approaching harvest.

Yields

Yields in 2015 were 10.5% less than 2014. About 6% less water was applied in 2015 than in 2014**,** but the lower ET and unanticipated rain in 2015 may have offset that difference. Our understanding is that the harvest volume was about the same in 2015 as 2014, but kernel weights were slightly lower for nonpareils and significantly lower for two other varieties. One possible explanation for the reduced kernel weights might be that early season (April and May) water supplies were higher than planned relative to late season water use. As a rule, water stress should be more or less balanced throughout the season (Shackel, personal communication), and some degree of stress early in the season would condition the trees to later stress. But unexpected rainfall and lower than expected potential ET resulted in high levels of crop available water until mid May, followed by significant stress through June. From Doll's graph in Figure 13, early season high crop water availability may have induced full growth of the outer shell early in the season, but the subsequent water supply was unable to support full growth of the kernels later in the season. We did adjust the plan in May to account for the anomalous weather, but perhaps not aggressively enough. There may also have been an echo effect from stress in the preceding three years of intensive drought.

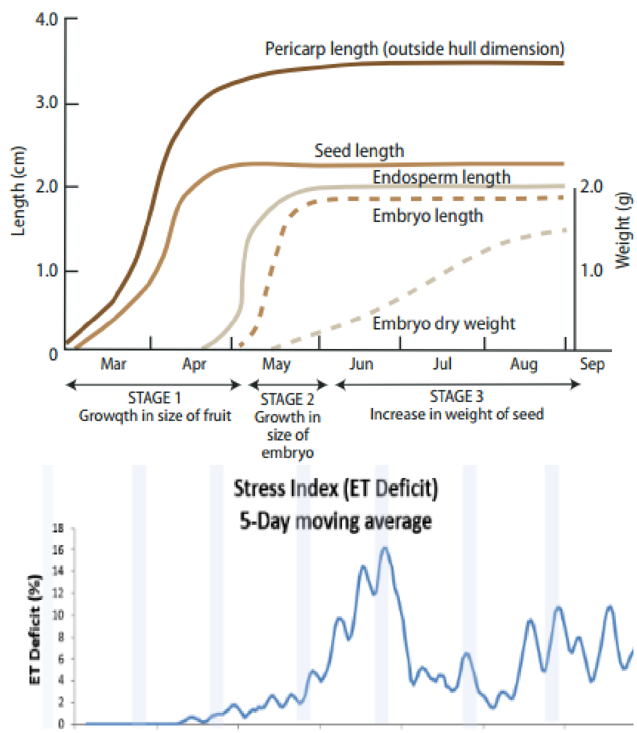


Figure 13. Comparing seasonal sensitivity to water stress to the seasonal pattern of estimated stress moisture with neutron probe data

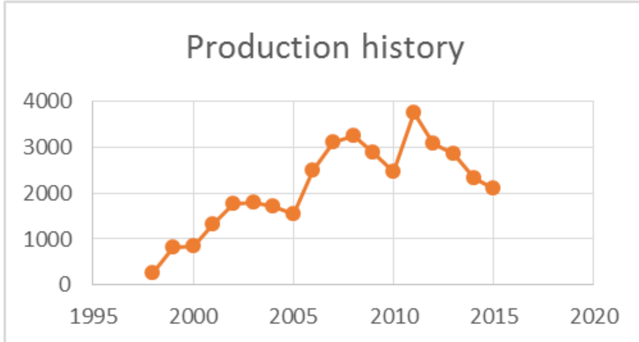


Figure 14. History of orchard yields since planting

CONCLUSIONS

Modeling of crop yields in response to partial irrigation, though intrinsically uncertain, provides science-based guidance for deciding how much water to allot to a particular field when water is limited or expensive. Example 1, illustrated value derived from modeling a field specific relationship between applied water and crop yields in order to examine in more precise detail the benefits of conserving water, and determine well defined optimal levels of water use.

Example 2 also illustrated the process of forward scheduling by which an irrigation manager was able to plan in detail for implementing a recommended irrigation strategy under drought conditions. The planning allowed the farm manager to envision an entire season.

The continuation of example 2 illustrated a necessary element of deficit irrigation management, the systematic and continuous processes of error detection and recalibration of the analytical system. The process of error detection, though predominantly based on the quantities that are modeled ((i.e. soil water depletion) can also be enhanced by systematically comparing independent sources of feedback data.
Comparison of uncalibrated and calibrated system analysis indicated that the error in initial estimates of antecedent moisture was about 3.5 inches, or 10% of the anticipated water supply.

The implementation of the intended strategy tracked well with the chosen strategy. The pattern of water use over the season was close to the originally stipulated pattern, after adjusting for the recommended increased water use approaching hull split. Yields were less than in previous years, but it is difficult to ascertain the cause.

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PROTECTING GROUNDWATER WITH SUBSURFACE DRIP IRRIGATION

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Claude J. Phene[2]

ABSTRACT

The groundwater resource in California is under severe stress due to the drought that increased pumping to meet crop and municipal demands previously met with surface water. Groundwater quality has been impacted from the movement of nitrates into the groundwater from fertilizers, decomposition of organic matter, and leaching of dairy wastes. Improving irrigation management will reduce the total water used to meet crop water requirements and deep percolation. With less deep percolation there will be less fertilizer losses through fertigation. High frequency subsurface drip irrigation has the advantage of placing the fertilizer within the crop root zone which improves fertilizer uptake. Both surface and subsurface drip irrigation can be operated multiple times a day to precisely meet crop water and fertilizer needs. We present the results of a study to determine the water and nitrogen requirement of mature pomegranate crop irrigated with high frequency subsurface drip (SDI) and high frequency surface drip irrigation (DI). We monitored the soil matric potential (SMP) in a weighing lysimeter that was irrigated with SDI. The SMP data over a period of 3 years showed there was no deep percolation loss below 5 ft with SDI. The water balance for the lysimeter confirmed that there was no deep drainage. There is wide acceptance of both DI and SDI in California on a wide range of crops.

INTRODUCTION

California has $1.36x10^6$ acres (ac) of irrigated land that is irrigated primarily with surface irrigation. The irrigation efficiency in California is generally higher than the world average (DWR 2009), however, the recent drought (2014) and environmental requirements have limited the availability of water to nearly 600,000 ac of land primarily in the Central Valley (San Joaquin and Sacramento Valleys) with nearly 250,000 acres being idled in 2014. Areas outside the Central Valley (Imperial, Coachella, Salinas, Napa, and Sonoma Valleys) are also water limited and rely extensively on groundwater as a significant supplemental supply to surface water and rainfall. Over the past 25 years there has been a significant shift in irrigation technology in California from surface to pressurized irrigation with a significant component being microirrigation including mini-sprinklers, micro-sprays, surface drip, and subsurface drip irrigation (SDI). SDI is the smallest component of microirrigation but is gradually gaining wider acceptance. Reviews of subsurface drip irrigation research are provided by Lamm, et al. (2007) and Camp (1998). One critical facet of the operation of an SDI system is the frequency of irrigation. Surface and sprinkler irrigation systems typically apply more water in a single

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irrigation and have irrigation schedules that provide water on a weekly or even longer time frame. However, both surface and subsurface drip systems are generally operated such that the irrigation frequency is increased to daily or near daily operation (Phene, et al. 1988). The implementation of higher frequency irrigation has resulted in improved yields and reduced percolation losses compared to surface and sprinkler pipe systems (Vázquez, et al. 2006).

As the scarcity of water has intensified in California and greater attention is placed upon irrigated agriculture to manage it, interest in SDI has also drawn attention from the fruit and nut, and alfalfa forage industries. Over 1.36×10^6 ac fruit and nuts (primarily, almond, walnut, pistachio, and stone fruits and approximately 1.00×10^6 ac of alfalfa are grown statewide. The fruit, nut, and berry farm's account for 47% of all farms in California and they produce 40% of the farm sales ($17 billion).

Pomegranate acreage in California increased to approximately 30,000 ac as a result of the demand for juices with healthy bioactive compounds, mineral nutrients, and high antioxidant contents. Despite this being an "ancient" crop, there are few studies quantifying the water and nitrogen requirements of a pomegranate orchard and none using either high frequency drip irrigation (HF-DI) or high frequency subsurface drip irrigation (HF-SDI). Research has shown that well managed HF-DI and HF-SDI systems can eliminate runoff, deep drainage, minimize surface soil and plant evaporation, reduce transpiration of drought tolerant crops, and significantly reduce fertilizer losses, thus protecting groundwater quality (Phene, et al.1989 and Ayars, et al. 1999). Avoiding N deficiency or excess is critical to maintaining nitrogen use efficiency (NUE) and knowledge of the operation of DI and SDI, especially for deep SDI, is critical for effective management of N-fertigation. This cooperative project was initiated in 2013 to determine the nitrogen fertilizer and water requirements of a maturing pomegranate orchard.

MATERIALS AND METHODS

The research was located on the University of California Kearney Agricultural Research and Extension Center (KARE) and used a 3.5 -ac pomegranate orchard (*Punica granatum, L* var. Wonderful) that included a large weighing lysimeter (Figure 1) (Phene et al., 1991). Trees were planted with 16 ft row spacing and a within row spacing of 12 ft. The orchard was laid out in a randomized complete block design with 2 main treatments and 3 sub-treatments with 5 replicates. The main treatments were DI and SDI (installed at 20-22-in depth) systems with drip irrigation laterals, located at 3.5 ft on each side of the tree row. The fertility sub treatments were 3 N treatments (50% of adequate N (N1), adequate N (N2), based on biweekly tissue analysis and 150% of adequate N (N3), all applied by variable injection of N-pHURIC (10% N as urea, 18% S), AN-20 (10% NH_4-N and 10% NO_3-N). Potassium thiosulfate (K_2T, 25% K from K_2O and 17% S) and phosphorus (from H_3PO_4, PO_4-P) were supplied by variable injection of P=15-20 ppm and K=50 ppm to maintain adequate uptake levels. The pH of the irrigation water was automatically maintained at 6.5+/-0.5. The lysimeter determined the water use for the fully irrigated (100%) subsurface drip irrigation (SDI) with adequate nitrogen (N2) treatment and automatically managed the hourly irrigation scheduling on the site. Water applied to the DI treatments was increased by 10% to account for evaporation from the soil surface and water used by weeds. There was one tree on the lysimeter and it was irrigated using a SDI system with the same number of emitters per tree as the rest of the orchard. Tree and fruit responses were determined by canopy measurements, bimonthly plant tissue analyses and fruit yield and quality. The fruit were harvested in a single harvest each year and separated into prime and subprime fruit. Prime fruit were characterized as being suitable for the fresh market with good red color and minimal surface cracking. Subprime fruit were used for the juice market and had deep surface cracking. Green fruit were counted and discarded. The number and weight of the fruit were determined for 5 trees in each replication and used for analysis. A split plot mixed model using the means taken over the trees was used in the analysis. Soil sampling was done each Spring before irrigation began and then in the Fall after fertigation had been completed. The profile was sampled to a depth of 48 inches in 6 inch increments in each replication and analyzed for nitrate nitrogen. The samples were averaged by depth across each treatment.

Reference evapotranspiration (ET_0) was taken from the California Irrigation Management Information System (CIMIS) weather station (#39) located on KARE Center. The crop water use (ET_c) was measured by the weighing lysimeter and was adjusted for field tree spacing. Precipitation came from the lysimeter weather station, drainage was measured in the lysimeter using a calibrated tipping bucket rain gauge, and there was no runoff. The applied water to the SDI and DI systems was measured with magnetic water meters.

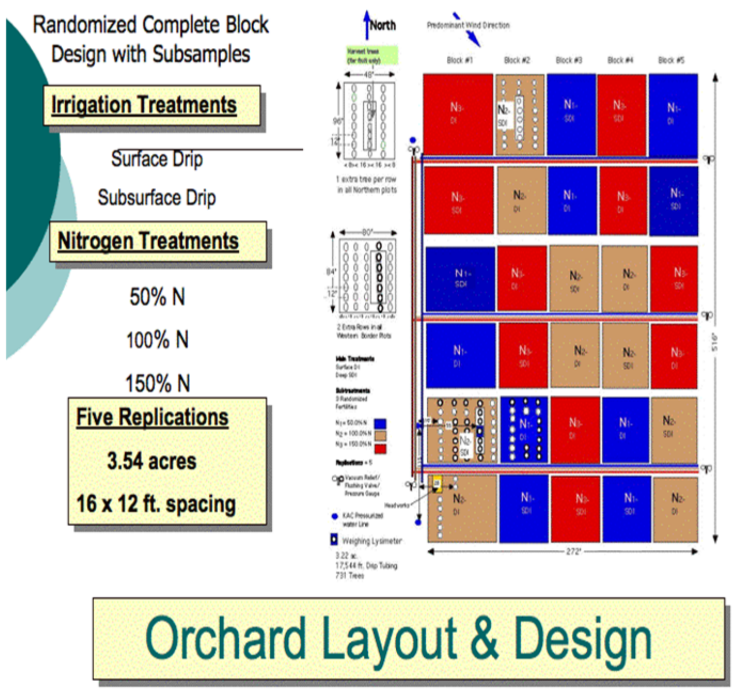

Figure 1. Orchard treatment, design and layout for surface drip irrigated (DI) and subsurface drip irrigated (SDI) pomegranate located at the KARE Center.

RESULTS

Pomegranate Water Balance

Table 1 gives the components of the water balance from 2010 until December 15, 2015. The first 2 years of data were included to characterize the crop development. The trees were removed from the field surrounding the lysimeter starting December 10, 2015. There was also cold weather prior to the tree removal that resulted in leaf drop and the cessation of transpiration.

The total annual reference evapotranspiration (ET_o) increased during the 6 years of the combined studies. From 2013 to 2015 there was approximately a 6% variation in the total ET_o. The rainfall values are below the regional averages of 10 in. due to the drought of the last 4 years. Most of the rainfall occurred during the winter which is typical for California.

Table 1.Yearly water balance data 2010 to December 15, 2015 for surface (DI) and subsurface (SDI) drip irrigated pomegranate measured with a weighing lysimeter irrigated with SDI.

Year	ET_o (in)	Precipitation (in)	DI (in)	SDI (in)	ET_c (in)	Drainage (in)
2010	49.7	17.3	1.0	1.0	2.1	n/a
2011	50.9	10.4	8.5	8.5	9.8*	0
2012	54.6	9.0	18.6	16.8	19.0	0
2013	55.0	3.2	25.4	23.0	26.9	0
2014	57.8	8.6	33.4	30.7	35.9	0
2015**	54.3	6.6	36.7	33.2	37.5	0

* ET_c measured from 5/1 – 12/8/11 only
** As of: Dec. 15, 2015

There was a uniform depth of applied irrigation water in 2010 and 2011 to insure good stand development and reasonably uniform plant size. The irrigation data for the DI and SDI systems shows a progressive increase in applied water to meet crop water use which was expected as the trees matured and increased in size over the six year period of the study. The difference in SDI and DI applied water beginning in 2012 was the deliberate addition of approximately10% more water to the DI treatment to compensate for water loss due to surface evaporation and water use by weeds. The last two years show that the crop water use is in the range of 36 in which reflects the mature crop water requirement.

The lack of drainage from the lysimeter was the result of high frequency irrigation with SDI. The ability to meet crop water demand with small applications of water minimizes the potential for deep percolation. With high frequency irrigation it is possible to control the soil matric potential and the resulting hydraulic gradients with the net result being no net deep percolation. Also, no drainage was measured with the tipping bucket rain gauge that measured drainage hourly from the lysimeter.

Soil Matric Potential (SMP) Measurements and Hydraulic Gradient Calculations in the SDI Irrigated Lysimeter

With the concern for transport of nitrate to the groundwater it is essential to quantify the movement of NO_3 through and below the crop root zone. We used heat dissipation soil water matric potential (SMP) sensors (Campbell Scientific Inc. CSI-229)[3] calibrated at 77°F at pressures ranging from 10 to 150 kPa (Phene et al, 1971a). These SMP sensors were installed in the lysimeter in two columns of SMP sensors installed at depths of 24, 36, 48 and 60 in. from the soil surface. The SMP sensors provided the SMP status in the lysimeter and were used to calculate the hydraulic gradient to determine the direction of water flow in the root zone and to infer the leaching potential under HF-SDI (Phene et al, 1989). Figure 2 gives the soil matric potential (SMP) at depths of 24 in., 36 in., 48 in. and 60 in. in 2013.

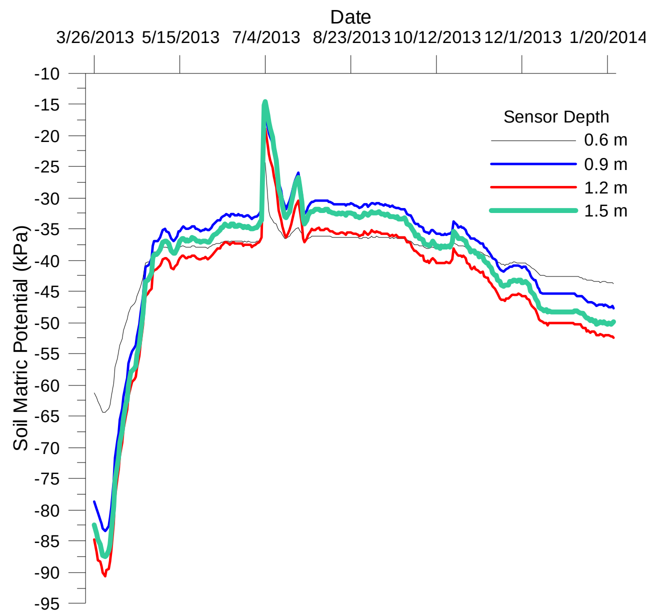

Figure 2. Daily average soil matric potential (SMP) sensor measurements from 3/24/2013 until 1/25/2014 in KARE weighing lysimeter.

The data show that the SMP was maintained in a range of -30 to -45 kPa which is a well-watered range for this Hanford sandy loam soil. The spike in the data in June of 2013 occurred when the irrigation was not controlled and excess water was applied. This also demonstrates the sensitivity of the sensors to changes in water potential. The hydraulic gradient was calculated using Darcy's law (1865) with the data from the SMP's

3 Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

$$\Delta H / \Delta Z = (H2 - H1)/(Z2 - Z1) \tag{1}$$

with $H = \Psi - Z$ where Ψ is the soil matric potential, H is the head, and Z is the depth.

This results in
$$\Delta H / \Delta Z = (\Psi_2 - \Psi_1)/(Z_2 - Z_1) - 1 \tag{2}$$

with $(\Psi_2 - \Psi_1)$ is the difference between 2 depths and the $(Z_2 - Z_1)$ is the soil depth difference measured downward from the soil surface and (-1) represents the gravitational component of the gradient. However, the downward flow due to gravity was insignificant due to the high frequency of irrigation with the HF-SDI systems. The unsaturated hydraulic conductivity is low due to the matric potential being maintained within the root zone. As a result the equation 2 reduces to

$$\Delta H / \Delta Z = (\Psi_2 - \Psi_1)/(Z_2 - Z_1). \tag{3}$$

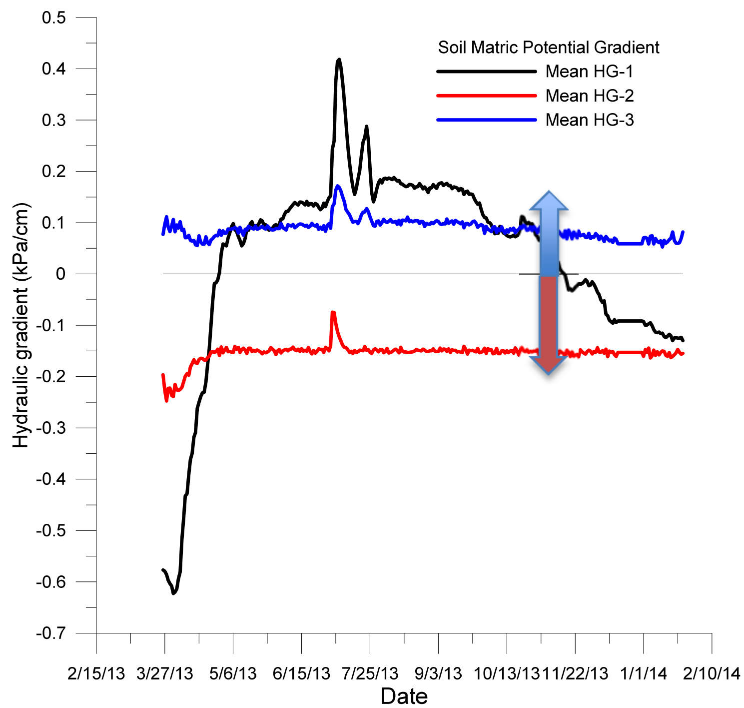

Figure 3. Soil hydraulic gradients (HG) calculated daily from 3/24/2013 until 1/25/2014 in KARE weighing lysimeter.

Calculated daily averaged soil matric potential gradients (SMPG) from 3/26/13 to 1/25/14 are shown in Figure 3 (SMPG > 0 indicates upward flux and SMPG < 0 indicate downward flux). SMPG-1 is the gradient from 24 to 36 in. SMPG-2 is the gradient from 36 to 48 in. and SMPG-3 is the gradient for 48 to 60 in. Results in Figure 6 indicate that SMPG-1 and SMPG-3 are positive with upward flow while the zone from 36 to 48 in. has water moving downwards. However, the gradient from 48 to 60 in. is upward thus preventing drainage and nitrate leaching (none measured from the lysimeter). Root uptake in the 36 to 48-in. depths is probably causing this SMPG behavior. The rise in hydraulic gradient starting on 7/4/13 resulted from a relay failure causing the irrigation pump to stay on for several hours (Murphy's Law) longer than required and resulted in excess irrigation. Despite the excess irrigation there was no drainage. These SMPG patterns would be expected to occur as well in the DI and SDI systems in the orchard.

The values for the average SMP for 2014 are given in Fig. 4 and the resulting hydraulic gradients are given Fig. 5. The changes in potential around day 80 in Fig. 4 were in response to a 1.3 inch rainfall. The subsequent decline in the potential was a result of the trees leafing out. This is followed by the beginning of irrigation and the trees reaching full bloom about day 110. The goal was to control the soil matric potential in the range of -30 to -45 kPa. This was done very successfully throughout the season. The periods outside of this range reflected instances when there were some problems with the water supply or the end of the season at harvest and finally when the system was shut down for the season. Note that in 2013 when there were problems with the irrigation system, the sensors responded quickly to the additional water which was the case with the rainfall.

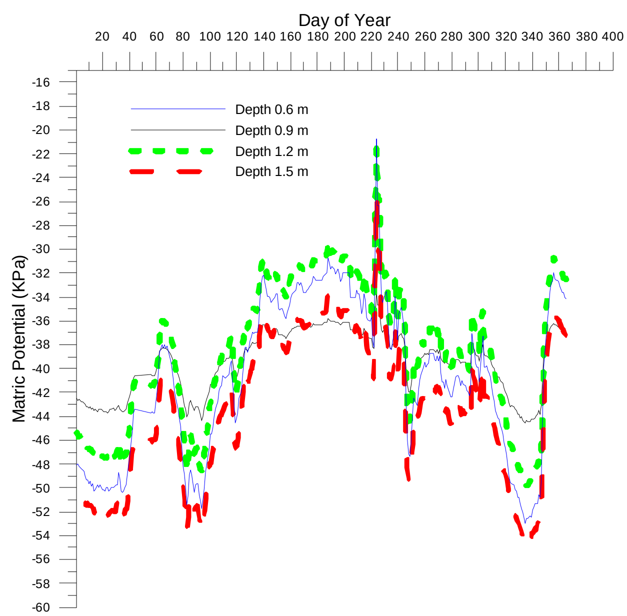

Figure 4. Daily average soil matric potential (SMP) sensor measurements in 2014 measured in KARE weighing lysimeter.

Recall that HG-1 is the zone from 24 to 36 in. depth, HG-2 is the zone from 36 to 48 in depth and HG-3 is the zone from 48 to 60 in. depth. The data show that there was a gradient of flow downward in the middle zone but continuously upward in the lowest zone. During most of the irrigation season the gradient and thus the flow was upward. The net result is that we controlled the flow within the root zone and no water and thus no nitrogen was lost to the groundwater.

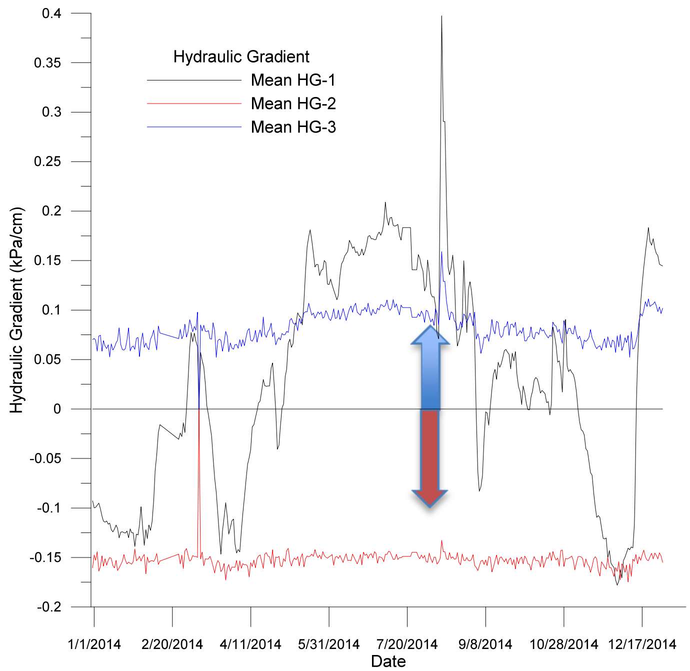

Figure 5. Soil hydraulic gradients (HG) calculated in KARE weighing lysimeter in 2014. The arrows indicate direction of flow.

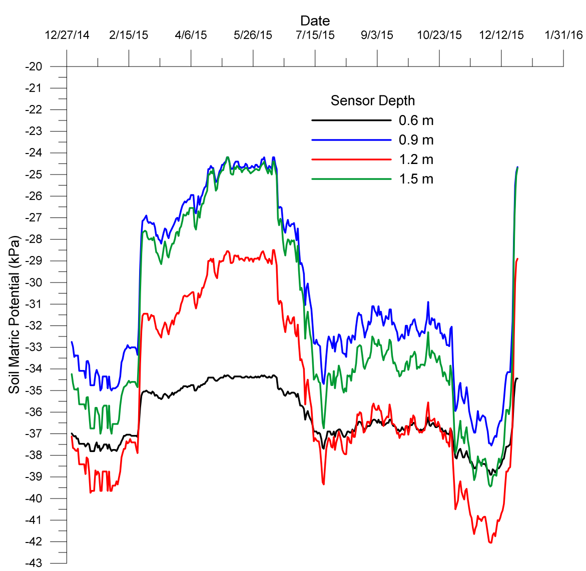

Figure 6. Daily average soil matric potential (SMP) sensor measurements in 2015 measured in KARE weighing lysimeter.

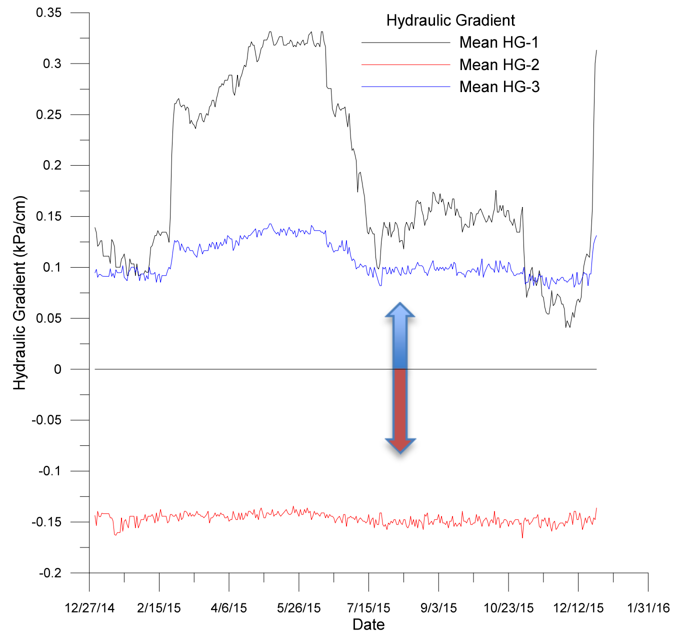

Figure 7. Soil hydraulic gradients (HG) in the KARE weighing lysimeter in 2015. The arrows indicate direction of flow.

The average SMP for 2015 in the KARE weighing lysimeter are summarized in Figure 6 and the hydraulic gradients's are given in Fig. 7. The same pattern is shown as was demonstrated in 2013 and 2014. The gradient in the zone from 36 to 48 in. (HG-2) is down while it is up in the zones above and below it. The net result is that there is no deep percolation loss from the root zone.

The transport of nitrate will be affected by the total applied nitrogen relative to the crop requirements. Nitrogen in excess will be available in the root zone and susceptible for transport. The total applied N, P and K for the 3 years of the study are summarized in Table 2. The resulting applied fertilizers provided a wide range of application to evaluate the response of yield to applied fertilizer and the potential for transport out of the root zone.

Table 2. Summary of applied nitrogen treatments (N1, N2, N3) and phosphorous (P) and potassium (K).

Year	N1 (lb./ac)	N2 (lb./ac)	N3 (lb./ac)	P (lb./ac)	K (lb./ac)
2013	62.3	148.5	218.3	58.5	65.0
2014	55.4	199.4	305.1	82.0	76.1
2015	100.7	235.1	295.9	103.6	161.6

The yield data are summarized Table 3 as averages across all nitrogen treatments for each irrigation system (SDI, DI) and across each irrigation system for the nitrogen treatments (N1, N2, N3). There were no statistical differences in the total yield by irrigation type or nitrogen level. The data demonstrate that approximately 100 lb/ac of nitrogen was adequate. Applications in excess of this were not productive. While not statistically significant the SDI average yield was higher in each year than the DI systems. Total yields increased each year because the tree size was increasing during this period as well.

Table 3. Summary of prime and subprime and total yields for 2013, 2014 and 2015 by irrigation system (DI and SDI) and nitrogen levels N1, N2, and N3.

Year	Irrigation System	Prime (lb./ac)	Sub Prime (lb./ac)	Total (lb./ac)	Nitrogen treatment	Prime (lb./ac)	Sub Prime (lb./ac)	Total (lb./ac)
2013	SDI	21934	9551	31485	N1	19320	10191	29511
	DI	20402	9250	29652	N2	21483	9381	30864
					N3	22815	8640	31455
2014	SDI	33366	9129	42495	N1	28181	12072	40253
	DI	29975	10511	40486	N2	30463	9603	40065
					N3	36367	7787	44154
2015	SDI	36533	8429	44962	N1	34510	11670	46180
	DI	30132	16291	46423	N2	33280	11810	45091
					N3	32206	13600	45806

Soil Nitrate Profiles

The fate of nitrogen and nitrate movement is a significant environmental concern in irrigated agriculture. The fate will be determined by both the placement and the total application of nitrogen fertilizers. Using SDI places nitrate below the soil surface and within the tree root zone while a DI systems applies the water and thus nitrogen to the soil surface. The effect of irrigation system on nitrate placement was measured using soil samples. Soil nitrate-nitrogen (NO_3-N) was measured every 6-in. from the soil surface down to 48-in depth in the spring and fall of each year.

The results for April 2013 and December 2013 are given Fig. 7 and 8. The data show that the NO_3-N levels are lower in the SDI system than in the DI systems at all depths. It also shows the effect of excess application of N on the concentrations with depth. As the applied values increased the concentration with depth increased. The average N by irrigation system in Fig. 7 B highlights the differences between DI and SDI on the usage and transport. The data in Fig. 8 for the December sample emphasize the effect more dramatically. Note that the NO_3-N concentration in the SDI systems is less than 10 ppm (EPA approved NO_3-N concentration for drinking water) which is not the case in the DI. The difference between systems is more pronounced in 8 B. In addition to the zero drainage measurements obtained in the lysimeter, these results indicate that the high frequency SDI system has the potential to eliminate or significantly reduce leaching losses of nitrates to the groundwater. The soil nitrate data from 2014 and 2015 revealed the same response between the levels of NO_3-N in the profile with DI systems having higher values than the SDI profiles. The NO_3-N concentration at a depth of 60 in was less than the 10 ppm of NO_3-N. Even the highest treatment levels of applied N had lower NO_3-N concentrations in the SDI systems than in the DI.

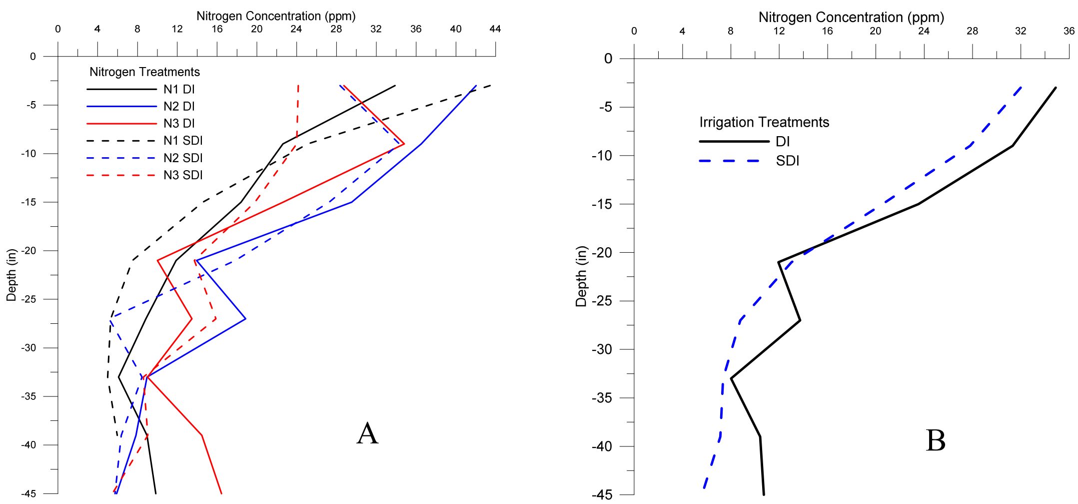

Figure 7. Soil NO_3-N measured every 6-in. from the soil surface down to 48-in depth on 4/2013 (A), before fertigation started in 2013. Average of nitrate by irrigation treatment in April 2013 for all nitrogen treatments (B).

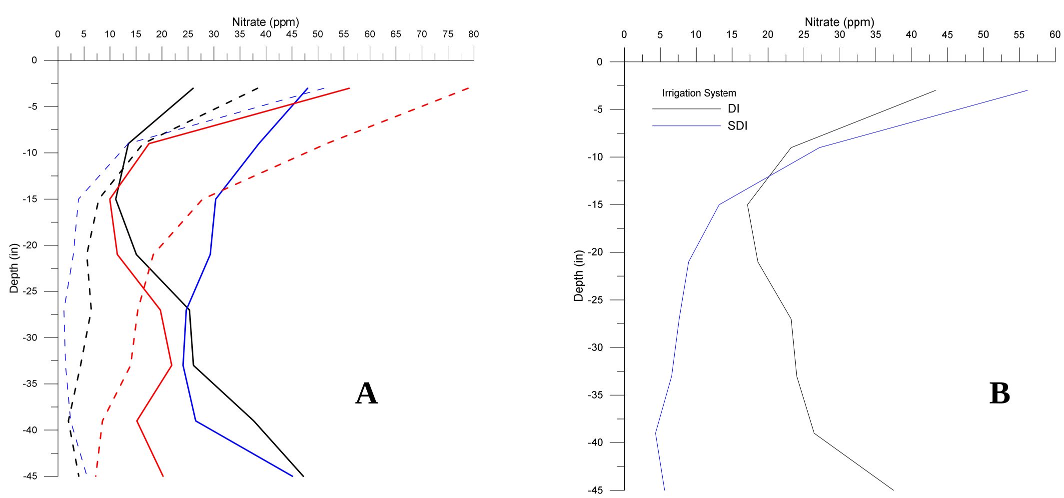

Figure 8. Soil NO_3-N measured every 6-in. from the soil surface down to 48-in depth on 12/2013 (A) averaged for all five replications. Average N by irrigation system for all nitrogen treatments (B)

CONCLUSIONS

The yield data for mature pomegranate demonstrated that 100 lb./ac provided yields equal to nitrogen applications in excess of 300 lb./ac. Applications in excess of 100 lb./ac will result in potential transport to shallow groundwater and wasted fertilizer. The soil NO_3-N data demonstrated that high frequency SDI was effective in minimizing NO_3-N transport below the crop root zone. Yields were higher in SDI systems than DI system.

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INCREASING WATER USE EFFICIENCY IN ALFALFA PRODUCTION THROUGH DEFICIT IRRIGATION STRATEGIES UNDER SUBSURFACE DRIP IRRIGATION

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ABSTRACT

Due to recurring droughts and water shortages in California, improved irrigation management strategies are necessary to sustain forage production under limited and impaired water supply. More efficient water application systems may allow implementation of deficit irrigation strategies during dry years. This paper presents preliminary data showing the potential benefits of deficit irrigation practices to increase water use efficiency (WUE) in alfalfa production utilizing subsurface drip irrigation (SDI). A field experiment was conducted at Davis, CA on a deep productive silt loam soil in 2014 and 2015. The irrigation treatments included 100% of crop evapotranspiration (ET), a late-season dry down that supplied 75% of seasonal ET; a mid-season dry down supplying 50% of seasonal ET, and a sustained deficit irrigation treatment starting at mid-season that supplied 75% of seasonal ET. The daily irrigations with SDI were scheduled on the basis of estimated full crop ET using eddy covariance instruments. Soil moisture and applied water were also monitored. Seasonal dry matter yield (average of 15 alfalfa varieties over eight harvests) for the full irrigation treatment was 10.1 ton ac^{-1} with an average WUE of 0.21 ton ac^{-1} in^{-1}. The WUE values increased to 0.28 and 0.33 ton ac^{-1} in^{-1} and yields were 95% and 80% of fully irrigated plots in the 75% and in the 50% irrigation treatments, respectively. High early-season productivity is a key reason for relatively low yield penalties at severe (50%) water cutbacks. Analysis of multiple-year variety trial results support significantly higher WUE in early vs. late season production, due to higher yields in early cuttings combined with moderate water demand. The higher yields under SDI compared to conventional flood and sprinkler irrigation and lower water cost of hay production in deficit irrigation practices may offset some adverse economic impacts of deficit irrigation. However, the seasonality of productivity of alfalfa which favors early, water-use efficient production enables deficit strategies to be developed for drought conditions under irrigation.

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INTRODUCTION

While alfalfa is one of the largest water users in western U.S. states, significant increase of water use efficiency may be realized through improved irrigation management practices. Subsurface drip irrigation (SDI) is a well-known feasible alternative irrigation technology with superior water application efficiency. Although SDI technology has been utilized primarily for high value speciality crops, its application has expanded to agronomic crops as the reliability and tape longevity has improved. A number of studies exist on applying SDI for forage crops including alfalfa (Hutmacher et al. 2001; Alam et al. 2002; Avila et al. 2003; Lamm et al. 2004; Berrada 2005; Lamm et al. 2005; Kieffer and Campbell 2009; Kazumba et al. 2010; Lamm et al. 2012; Ismail and Almarshadi 2013).

SDI may reduce total water application and increase hay yields, thus generating significant benefits on the economic profitability and water productivity of alfalfa production. More uniform water distribution over time and space during the growing season reduces the amount of water stress on alfalfa and causes rapid re-growth and higher yields (Putnam et al. 2015). Alfalfa hay yield in SDI system was found approximately 22% (Hutmacher et al. 2001) to 25% (Godoy et al. 2003) higher than that of flood irrigated fields. Other benefits of SDI identified by researchers are the possibility to shorten the intervals between cuttings and increase the number of cuttings, provide longer stand life and develop healthier root systems, improve the uniformity of crop growth, and control weed due to dry soil surfaces (Hutmacher et al. 2001; Hengeller 1995; Alam et al. 2002; Lamm et al. 2012).

Deficit irrigation has been widely investigated as a valuable and sustainable production strategy over a wide variety of crops. The overall effect of deficit irrigation in terms of water productivity largely depends on the type of crop and the adopted irrigation strategy. Although frequently criticized for its high seasonal water use requirement, alfalfa has very positive biological features, including greater yield potential than many other legume crops under water stress (Peterson et al. 1992). If alfalfa water allotments are significantly curtailed, the development of progressive water stress to the crop will result in reduced evapotranspiration, CO_2 exchange, symbiotic N_2 fixation, and dry matter yield (Kirkham, 1983). While there is a positive relationship between alfalfa yield and ET (Grimes et al., 1992), during droughts yields are not always reduced in direct relation to the reduction in applied water (Ottman 2011; Orloff et al. 2005).

Jensen and Miller (1988) indicated a WUE range of 0.13-0.17 ton ac^{-1} in^{-1} on alfalfa in Nevada. Hanson et al. (2007) reported alfalfa WUE of 0.14 and 0.10 ton ac^{-1} in^{-1} under border irrigation in the San Joaquin Valley, CA and Imperial Valley, CA, respectively. Average annual WUE values may vary between 0.11 and 0.26 ton ac^{-1} in^{-1} (Grimes et al. 1992; Hirth et al. 2001) depending on environmental condition and on the alfalfa variety.

Several studies have investigated the effect of mid-summer irrigation cut-off (no irrigation after June until the following spring) on alfalfa yield. Ottman et al. (1996) found that yield under mid-summer deficit irrigation in Arizona was very low and did not recover in sandy soil, but summer termination (July through October) had less dramatic effect on sandy-loam soils. At a site in the San Joaquin Valley, yields of a mid-summer irrigation cut-off treatment were 65–71% of that of a fully irrigated treatment over a 2-year period (Frate et al. 1991). Mid-summer deficit irrigation in the Imperial Valley of California reduced yields to levels of 53–64% of that of fully irrigated alfalfa (Robinson et al. 1994). Mid-summer deficit irrigation reduced yield to 46% of the fully irrigated treatment in the Palo Verde Valley of southern California (Putnam et al. 2000). Significant yield reductions resulted from deficit irrigation over a 3-year period in a study conducted in Nevada, but yields were recovered under adequate irrigation during the fourth year (Guitjens 1993). Annual alfalfa yields under SDI were unaffected by 20 and 30% sustained deficit irrigation over the season in a study conducted at Northwest Research-Extension Center, Kansas State University (Lamm et al. 2012). In this experiment, rainfall had a major contribution to the crop water use, with precipitation contributing about 25% of seasonal crop water use between June and October.

These studies showed that applying zero irrigation during the mid-summer reduced the alfalfa yield, but generally did not result in plant death, which would necessitate re-establishment of the crop. Economically, although yield losses due to water deficits can be important, the costs of re-establishment of the plant stand are not trivial and a major risk associated with deficit strategies. As a general strategy, during times of reduced water supplies it is important to consider the seasonal production patterns of alfalfa and maximize production during early growth periods, and allow water deficits during periods of relatively low yield and quality, e.g. late summer. Although these concepts have been demonstrated in several irrigated regions of California (Orloff et al. 2005; Orloff and Hanson 2008; Hanson et al. 2008; Putnam 2012), there has been virtually no research work conducted on deficit irrigation under SDI in alfalfa. This study provides preliminary results on the effect of different mid-summer deficit irrigation strategies on alfalfa yields and water use efficiency under SDI.

FIELD EXPERIMENTS

We conducted field trials on a deep productive silt-loam soil with a saturation percentage of 47% at Davis, CA during 2014 and 2015. The experiments are part of an ongoing three-year project started in October 2014 and to be continued through 2017. Fifteen commercial or newly-released alfalfa varieties to be potentially grown in the Southwest US (Arizona, California, and New Mexico) were established. Trials were set up in a randomized complete block design with a split plot restriction. Four replications were established for each sub-plot with the size of 18×4 ft. Germination was achieved using sprinkler irrigation. The soil profile was refilled by sprinkler irrigation during early season growth in 2014-15, and afterward starting April 19, 2015, the trials were irrigated by SDI during the entire season, with 40-in spaced driplines installed 10-12-in deep, and equipped with 14-in spaced emitters. The driplines are of commercial type (Typhon 875 series) with inner diameter of 0.875 inches and regularly spaced emitters with nominal flow rate of 0.18 gph at 10 psi.

The irrigation treatments included irrigation I (IRI, full irrigation at 100% of crop ET), IRII (full irrigation until late-season dry down (sudden cutoff on August 18, 2015) supplying 75% of seasonal ETc over the year), IRIII (full irrigation until 50% of seasonal ET occurred July 2, 2015, and then 50% sustained deficit irrigation for the rest of the season, supplying 75% of seasonal ET over the year, and IR-IV (mid-season dry down at 50% of ET (sudden cutoff on July 2, 2015) starting in July 2nd). At full irrigation treatment, 100% of crop water requirement was supplied, following ET-based irrigation scheduling. The full alfalfa ET was measured at a nearby experiment in Davis using the residual of energy balance method with Eddy Covariance instruments – the daily crop coefficient (K_c) values were adjusted based upon the changes observed during each cutting schedule – with the summed K_c values totaled approximately 0.85 of ET_o directly from our Eddy Covariance readings for the fully irrigated treatment

The dates of start of deficit irrigation in the deficit trails were determined using long-term average weather data from the CIMIS, California Irrigation Management Information System, station No. 6 (Davis) and the long-term average of alfalfa water use (ET).

To reproduce the common irrigation practices followed by alfalfa growers, we suspended irrigation for a period of 9-10 days around each cutting, usually 4-5 days before and after each cutting. Soil moisture monitoring was conducted using resistance blocks (Watermark) installed at the four sub-plots. The soil moisture sensors were used to measure soil water tension in the different irrigation treatments at the depths of 8, 20, 30, and 48 inches and at the distances of 10 and 20 inches from the drip tape. At each subplot, eight soil moisture sensors were connected to a data logger (Irrometer 900M), which was programmed to log data every 30 minutes. The applied water was measured and monitored over irrigation events using multi-jet impeller water meters (Netafim type M) enabling an accuracy of 2% over a wide range of flows. Yields at each cutting were measured using a Swift Current experimental plot harvester, adjusted for dry matter (DM) utilizing field samples, and calculated on an acre basis.

RESULTS AND DISCUSSION

Alfalfa ET and Irrigation Distribution

The 2015 irrigation season occurred during the 3rd consecutive year of extreme drought in California, with an average air temperature of 69^{o}F, total rainfall of 2.19 in, and average air relative humidity of 52% between April and October (Table 1). The total annual precipitation was 7.1 inches, corresponding to about half of the historical annual precipitation of the area. The annual cumulative ET_o and alfalfa seasonal ET were estimated at 58.9 and 47.0 inches, respectively, for the entire year, but alfalfa ET was approximately 40 inches during the irrigation season.

The estimates of alfalfa daily ET and daily applied water (irrigation+ effective rainfall) in full irrigation treatment over the season are presented in Figure 1. The total rainfall during the growing season was considered as effective rainfall. The K_c values varied between 0.36 the day after cut and 1.07 at full canopy cover within each growing cycle, with a total of 8 cycles, based upon our Eddy Covariance data. The average daily alfalfa ET was 0.2 inches, but ranged between 0.04 and 0.37 inches. The temporary dry down at cutting events can be clearly observed from Figure 1. In details, a 9 to10-day dry period was induced at every cycle, due to the need to dry the field down to allow for harvest.

Table 1. Monthly mean climate data for CIMIS #6 station in 2015

Month	Rain (in)	Solar radiation (Ly day^{-1})	Avg. Mean air temp (°F)	Ave. Relative Humidly (%)	Dew point temp (°F)	Mean wind speed (mph)	Total ET_o (in)
Jan	0.06	214	48.2	84	43.3	3.7	1.53
Feb	2.67	302	54.5	76	46.5	5.1	2.36
Mar	0.25	440	59.6	62	46.1	4.6	4.44
Apr	0.91	584	60.7	52	42.1	6.2	6.2
May	0.02	651	62.8	59	48.3	6.6	7.06
Jun	0	697	73.6	51	54	5.3	8.14
Jul	0	660	74.7	52	55.2	6.1	8.35
Aug	0.01	605	73.8	50	53.3	5.2	7.46
Sep	0.07	469	71.2	45	47.4	5.1	5.67
Oct	0.19	345	67.8	52	49	4.7	4.21
Nov	1.48	243	50.1	66	38.4	5.2	2.22
Dec	1.45	161	46.7	78	39.8	5.7	1.28
Total	7.1	-	-	-	-	-	58.9
Mean	-	447.6	62.0	60.6	47.0	5.3	-

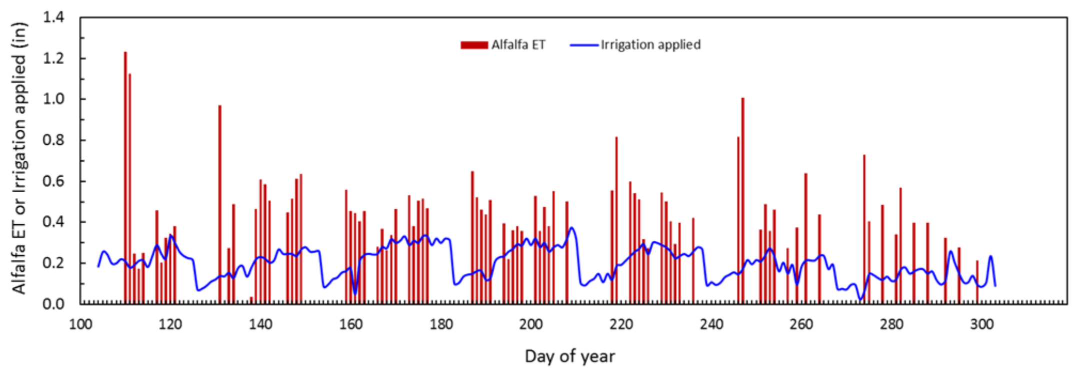


Figure 1. Daily alfalfa ET and applied water at the full irrigation treatment

Figure 2 presents the comparison between the cumulative irrigation applied at different treatments with the cumulative alfalfa ET over the season. The total alfalfa ET under full irrigation (IR I) was 39.9 inches. As it can be seen, the SDI system enabled a good match between water application and crop ET for the full irrigation treatment. This is one of the advantages of SDI system in alfalfa fields, where a good irrigation control allows matching crop ET over the growing season. If the concern associated with the necessary dry down periods before and after each harvest is addressed, a better irrigation distribution over time is possible with SDI. The total applied water at the treatments IR I, IR II, IR III, and IR IV over the irrigation season were 39.9, 29.5, 30.4, and 19.0 inches, respectively. The rest of annual crop water requirement was supplied by the 2015 rainfall and fall 2014 rainfall.

Soil Moisture Status

The moisture sensors were located within the effective root zone at locations providing a representative picture of the soil water status of the experimental plots. Figure 3 depicts the soil water tension at the experimental plots of full irrigation and 50% deficit irrigation over the irrigation season for different depths and distances from the driptapes. The figure shows that soil moisture was maintained pretty uniform at different depths below driptapes over the season at the full irrigation treatment (Fig. 3). The shallow sensor (20 in depth) was the most affected by irrigation events, as sensor's readings varied between 8 and 25 centibars (cb) at the distance of 10 inches away from driptape, and between 18 and 40 cb at 20 inches away from driptape. During the temporary dry down periods around cuttings, the soil water tension showed an average drop of 15 cb, and then started to increase to approximately field capacity after irrigation started. Overall, highest soil moisture tension was observed at the sensors located at farther distance from the drip tape, and specifically at the sensor installed 20 inches deep.

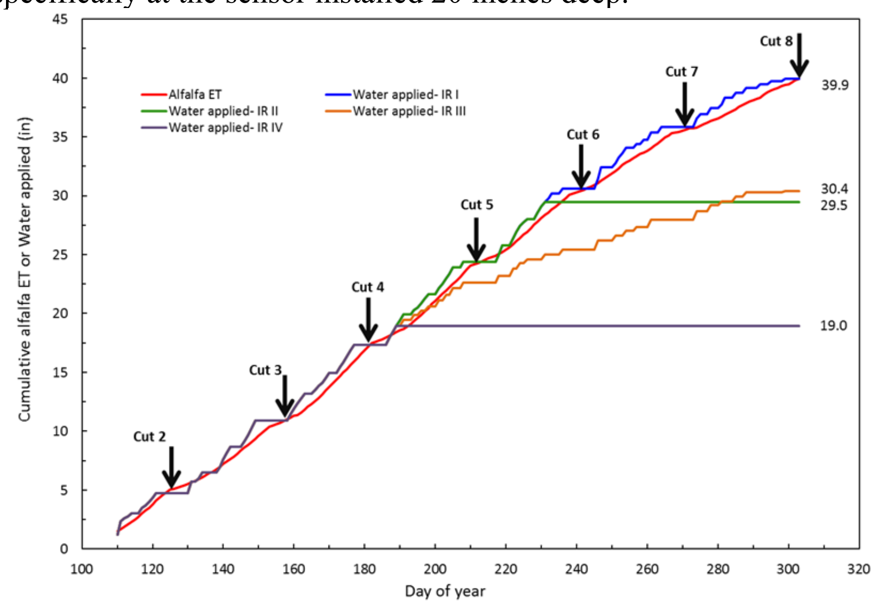


Figure 2. Cumulative alfalfa ET and applied water at the different irrigation treatments over the season 2015

The average soil moisture tension values measured at the depths of 20, 30, and 48 inches at distance of 10 inches from the drip tape over the growing season were 17, 14, and 16 cb, respectively. These tension readings reveal the efficiency of SDI in maintaining adequate soil moisture over time. The soil water tension readings show that soil has been adequately wet during the entire irrigation season, and that moisture was effectively maintained in the crop's root zone in a way to provide desirable plant available water without water stress at the full irrigation treatment. For most soils, alfalfa will not incur water stress when soil water tension is between 5 and more than 60 cb. Recommended soil water potential for alfalfa in a silt loam soil should be within the range of 10 to 60-90 cb (Table 2).

Soil moisture was clearly impacted by deficit irrigation just a few days after irrigation was cut-off (Figure 4), when the soil moisture tension reached a severely dry status (239 cb) after 50 days at 20-inch depth, 72 days at 30-ichnch depth, and 59 days at 48-in depth. The day after the start of deficit irrigation, soil water tension was 16 cb at 20-inch depth, 19 cb at 30-inch depth, and 17 cb at 48-inch depth. The soil water tension values indicate that the crop's root zone had adequate available water at the time deficit irrigation was started and the plant was able to extract water from the residual soil moisture without incurring any water stress during the first 20-25 days after irrigation was stopped (Figure 4).

Table 2. Recommended maximum soil moisture tension allowable for different soil types (Orloff, 2005)

Soil type	Soil moisture tension (centibar)
Sandy or loamy sand	40-50
Sandy loam	50-70
Loam	60-90
Clay loam or clay	90-120

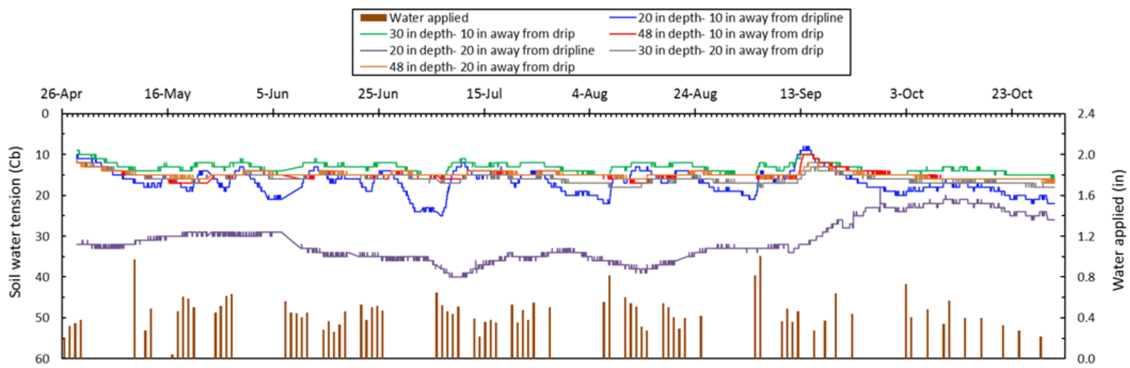


Figure 3. Soil water tension variations over the season at different depths at 10-inch distance from drip tape (full irrigation treatment

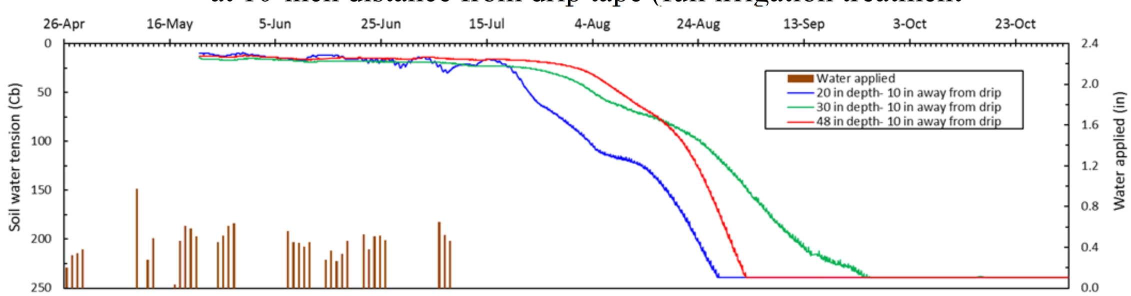


Figure 4. Soil water tension variations over the season at different depths below dripline (50% deficit irrigation treatment)

While irrigation events showed some effects on the soil moisture of the shallower layer, the soil water tension above the drip tapes (8 in depth) continuously increased so that an average soil water tension of 175 cb was recorded at end of the season (Figure 5).

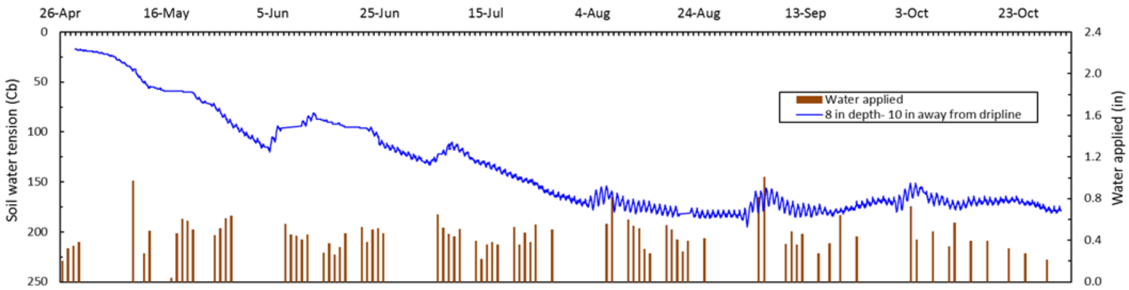


Figure 5. Soil water tension variations over the season above the driptape (full irrigation treatment)

Alfalfa Dry Matter

The alfalfa dry matter and cumulative yield percentage values (averaged over 15 alfalfa varieties) over the seasonal cuttings for each irrigation treatment are illustrated in Figure 6. The results showed that the highest and lowest dry matter per cut were observed in the second cut (for instance, 1.63 ton ac^{-1} for the full irrigation treatment) and the last cut (for instance, 0.62 ton ac^{-1} for the full irrigation treatment), respectively (Figure 6a). A total of 74.1% of seasonal dry matter was obtained over the first five cuts until the end of July; and 12.1% in the 6th cut, 7.7% in the 7th cut, and 6.2% in the 8th cut (Figure 6b). Figure 6a clearly shows that spring and early-summer cuttings result in higher alfalfa yields. The average alfalfa DM of 15 varieties over eight cutting events at the irrigation treatments of I, II, III, and IV were 10.05, 9.67, 9.55, and 8.14 ton ac^{-1}, respectively (Figure 7).

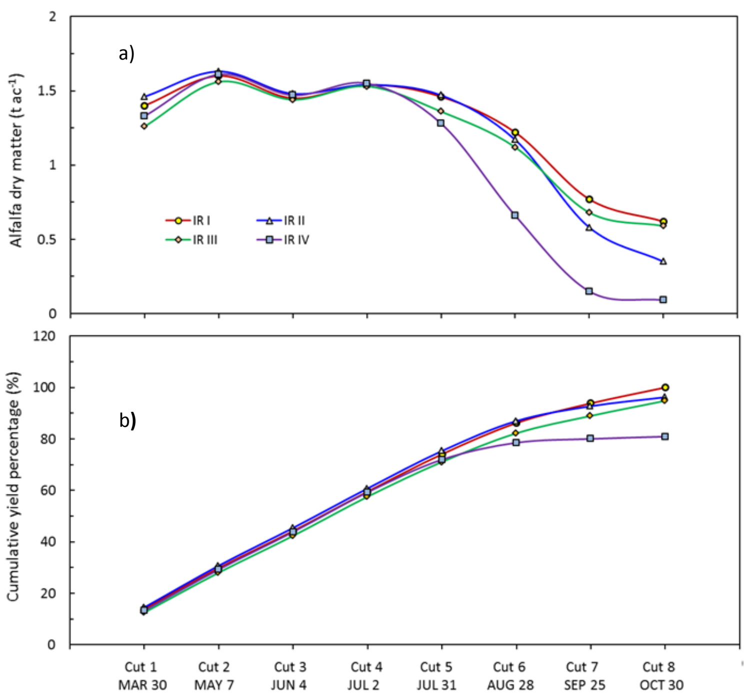


Figure 6. Alfalfa dry matter and cumulative yield percentage at different irrigation treatments over the seasonal cuttings

The cumulative yield percentages match pretty well the results obtained from other studies conducted on alfalfa fields under conventional flood and sprinkler irrigation. Orloff et al. (2015) concluded that approximately three-fourths of the total alfalfa annual production occurs by mid-July in the Sacramento Valley. Figure 8 shows that the long-term cumulative alfalfa yield percentage over the growing season were 73% and 75% in Fresno County and Siskiyou County, respectively (average of all varieties at each site – data reported at http://alfalfa.ucdavis.edu/+producing/variety/.

Although yield reductions occurred right after irrigation was cut off (IR IV) by early July, only a reduction of 5.5% occurred at the 6th cut. This indicates that some plant growth continues even after severe irrigation cutbacks thanks to residual soil moisture. No difference in terms of yield reduction at the end of the year was found for the 75% irrigation scenarios, where reduction were 3.8% at IR II and 5.0% at IR III were observed (Figure 7). A 19% yield reduction was observed for the 50% deficit irrigation scenario over the year, mostly from the last four cuttings of the growing season, which were affected by severe water limitations.

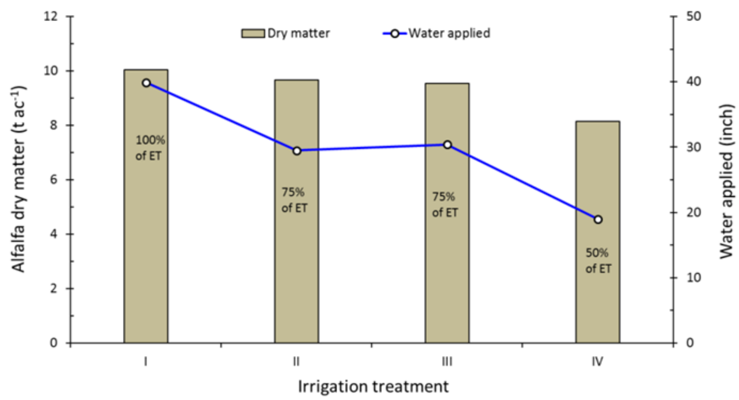


Figure 7. The average alfalfa DM of 15 varieties over the growing season and water applied for different irrigation treatments

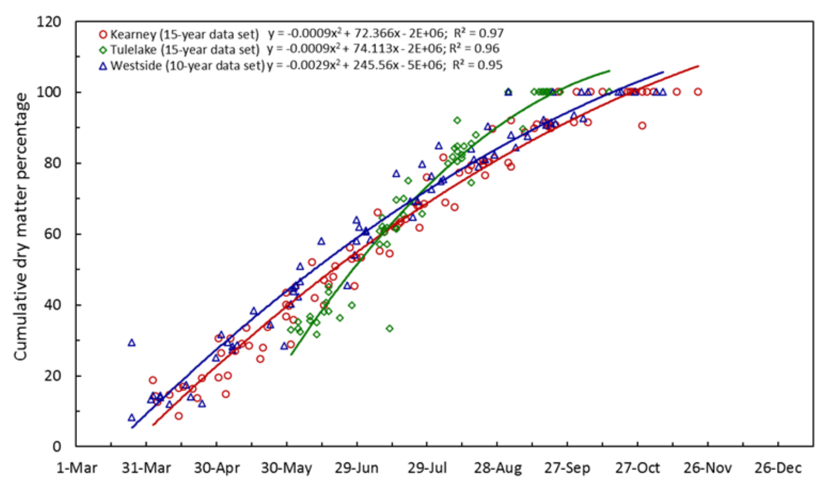


Figure 8. Long-term cumulative multi-variety alfalfa yield percentage over the growing season in California

Here, the efficiency of deficit irrigation strategy was defined as the ratio of reduced applied water percentage to yield reduction percentage obtained as a result of deficit irrigation strategy. This dimensionless indicator shows the efficiency of deficit irrigation practice in terms of yield penalty and reduced applied water, in which a higher value reflects a greater efficiency of strategy. Figure 9 illustrates the values of this indicator for all three deficit irrigation strategies. The comparison of the values for the deficit irrigation practices reveals that the late-season dry down practice of 25% deficit irrigation with a value of 6.9 had a better efficiency than the other practices, followed by the 25% sustained deficit irrigation from mid-season with a value of 4.8. Although the analysis shows all three deficit irrigation practices had significant impacts on reduced applied water and high yield, the 50% deficit irrigation practice had the lowest performance with the indicator resulting in a value of 2.8.

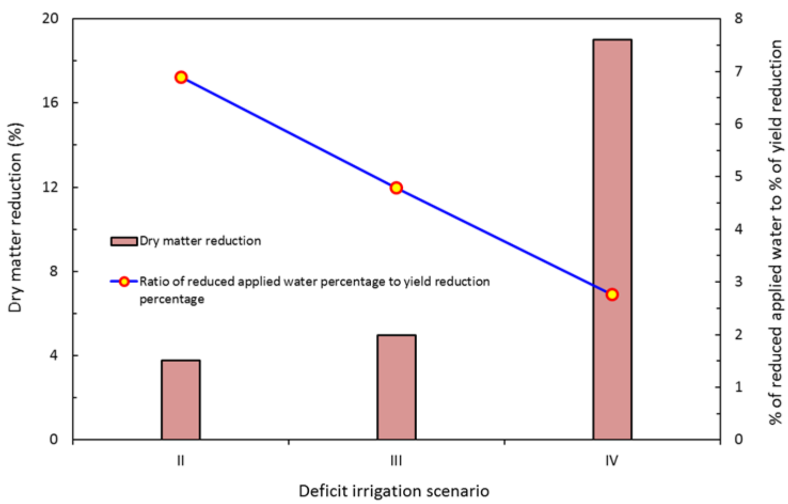


Figure 9. Dry matter reduction and ratio of reduced applied water percentage to yield reduction percentage for the deficit irrigation practices

Water Use Efficiency

Generally speaking, water use efficiency is the efficiency by which crop converts the transpired water into economic dry matter yield. Alfalfa WUE was computed for the average for the different varieties for the different irrigation scenarios (Table 3). The averaged WUE value over all the 15 varieties with full irrigation was 0.21 ton ac^{-1} in^{-1}, which matches with the average value predicted for alfalfa production under SDI in the Central Valley and Imperial Valley as indicated by Montazar et al. (2016). The results indicate that alfalfa WUE can be significantly affected by the different deficit irrigation regimes. Deficit irrigation effectively increased alfalfa WUE. For instance, a 53% increase of WUE (0.33 ton ac^{-1} in^{-1}) was observed for the 50% deficit irrigation treatment. The WUE value resulted in increases of 28% and 23% for the IR II and IR III (25% deficit irrigation treatments) as compared to full irrigation.

A greater WUE may be achieved under SDI-irrigated alfalfa compared to flood and sprinkler irrigation. Hanson et al. (2007) reported an alfalfa WUE of 0.14 and 0.10 ton ac^{-}

^{1} in^{-1} under border irrigation in the San Joaquin Valley and Imperial Valley, respectively. A comparison between the results obtained in this study and findings obtained by Hanson et al. indicates that implementing a desired deficit irrigation strategy with higher-efficient irrigation systems such as SDI may improve alfalfa WUE up to 100% relative to that resulting from the current irrigation practices in California. This could have significant benefits on alfalfa production sustainability during the recurrent droughts and water limitations.

Figure 10 shows the WUE values of each seasonal cutting for the full irrigation treatment. Since applied water and crop ET were in a significant match over growing season, the amounts of applied water during each cutting cycle were used for the calculation. No irrigation occurred over the first cycle up to the first cutting. The crop water use of the first cut was estimated utilizing an average K_c value of 0.85 and total ET_o between February 1st and March 30th when the first crop cycle and cutting were realized. We found that a polynomial regression curve as the one shown in Figure 10 can well represent the alfalfa WUE inverse trend over the seasonal cuttings. The WUE of the 7th and 8th cuttings were 0.15 and 0.13 ton ac^{-1} in^{-1}, respectively, and those values are lower than the WUE of all other previous cuts. The negative trend of alfalfa water use efficiency with the progressive cuttings along the crop season under conventional irrigation methods in California has been already reported by Orloff et al. (2015), who documented changes in alfalfa water use efficiency over the growing season between 0.09 and 0.16 ton ac^{-1} in^{-1} for surface and sprinkler irrigation in the Sacramento Valley. The higher WUE in spring and early summer can be related to higher yields and lower crop water use during these periods than summer. As a result, and consequently the water use efficiency is greater in earlier cuttings than that of mid-summer and fall.

Table 3. Values of water use efficiency obtained for the different irrigation treatments

Irrigation treatment	IR I	IR II	IR III	IR IV
WUE (ton ac^{-1} in^{-1})	0.21	0.28	0.27	0.33

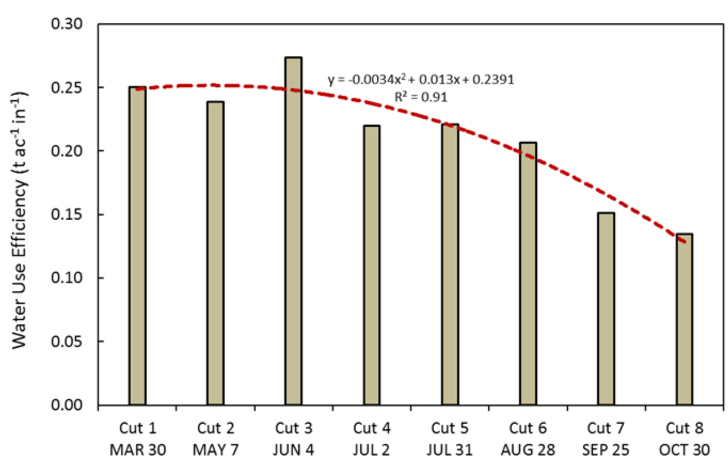
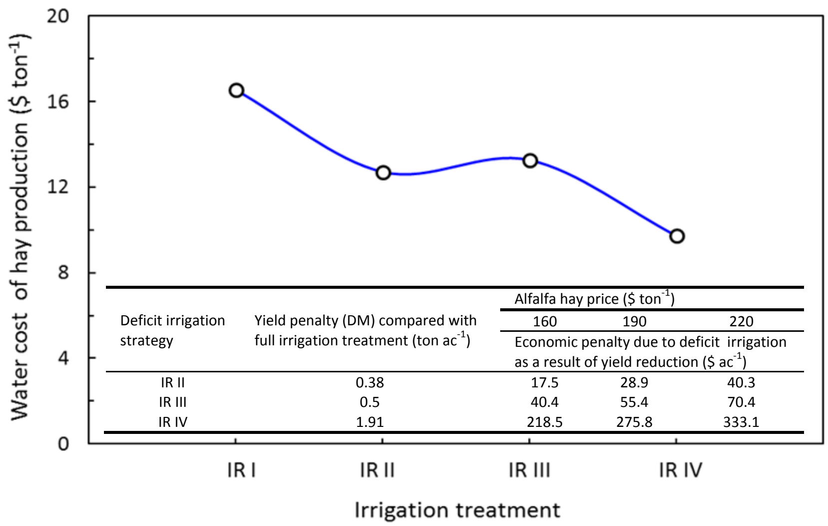


Figure 10. Alfalfa WUE over the different cuttings along the crop season in full irrigation treatment

Preliminary Economic Considerations

A preliminary economic analysis was conducted using hay yields and applied water in each of the irrigation treatments. The full irrigation treatment had a DM of 0.38 ton ac^{-1} higher than IR II, 0.5 ton ac^{-1} higher than IR III, and 1.91 ton ac^{-1} higher than IR IV. The amount of applied irrigation water over the irrigation season at irrigation treatments I, II, III, and IV were 3.33, 2.46, 2.53, and 1.58 ac-ft, repsectively, not including rainfall contributions before the irrigation season. Assuming \$50 $(ac\text{-}ft.)^{-1}$ as an average water cost, the lower water cost resulting at the different deficit irrigation scenarios relative to that of full irrigation was estimated at \$43.30 ac^{-1} for the 25% with a late-season dry down scenario, \$39.60 ac^{-1} for the 25% with partial irrigation started at mid-season scenario, and \$87.10 ac^{-1} for the 50% with mid-season dry down scenario (Figure 11). All the deficit irrigation practices had yielded less hay when compared to hay yields of fully irrigated alfalfa. Considering an alfalfa hay price of \$190 ton^{-1} for good quality hay, this lower benefit was determined to be \$72.20, 95.0, and 362.90 $ac^{-1}$for IR II, IR III, and IR IV, respectively. Results for the alfalfa hay price of \$160 and 220 ton^{-1} were also shown in Figure 8. In terms of water cost, as one of the major variable costs over an alfalfa growing season, to produce a unit of hay yield, the deficit irrigation practices showed a significant economic benefit. The ratio of water cost to hay yields was \$12.70 ton^{-1}, \$13.30 ton^{-1}, and \$9.70 $ton^{-1}$for IR II, IR III, and IR IV, respectively, which demonstrates that all of the deficit irrigation strategies have lower water cost per unit of hay than full irrigation treatment (\$16.5 ton^{-1}), Figure 11. Consequently, the economic penalty as a result of yield reduction in deficit irrigation scenarios is reduced to \$28.90 ac^{-1} for the irrigation treatment II, \$55.40 ac^{-1} for the irrigation treatment III, and \$275.80 ac^{-1} for the irrigation treatment IV with an average alfalfa hay price of 190 ton^{-1} (Figure 11).

Higher alfalfa hay yields are achievable with SDI and and lower water cost of hay production in deficit irrigation practices may allow offsetting some of the adverse economic impacts of deficit irrigation. An average alfalfa hay yield increase of 2.6 ton ac^{-1} in farms utilizing SDI compared to farms under conventional flood irrigation has been reported from an on-going study with the University of California (Putnam et al. 2015). Consequently, desired deficit irrigation strategies in alfalfa production might be still considered as a profitable management tool for a high initial investment cost irrigation system such as SDI.



Deficit irrigation strategy	Yield penalty (DM) compared with full irrigation treatment (ton ac^{-1})	Alfalfa hay price ($ ton^{-1})		
		160	190	220
		Economic penalty due to deficit irrigation as a result of yield reduction ($ ac^{-1})		
IR II	0.38	17.5	28.9	40.3
IR III	0.5	40.4	55.4	70.4
IR IV	1.91	218.5	275.8	333.1

Figure 11. Comparison of water cost of hay production and economic loss due to deficit strategies compared with full irrigation practices

CAVEATS AND DISCUSSION

Several cautionary notes need to be considered with the data reported and the analysis accomplished in this article:

- The reported data is from a single location and a single year on Class I soils. It is highly likely that different results would be expected on different soil types, especially in very sandy soils.
- The estimates of full ET were calculated using scientific methods; however it is still possible that the full irrigation treatments received greater than the full needs of the crop, making the result of deficit treatments look better than one would expect.
- The alfalfa actual ET was estimated from sprinkler irrigated systems using long-term data – it is possible that the true alfalfa actual ET for subsurface drip is different than that of surface irrigated alfalfa crops. Further research is being conducted on this matter.
- The influence of residual moisture from the previous year also requires further consideration.
- In this experiment, the plant stand was excellent after one year of deficit irrigations in all treatments, but it is uncertain whether multiple years of deficit irrigation would threaten the long-term viability of the crop.
- The role of deliberate re-filling of the soil profile after deficits need to be considered both in terms of water availability and policy. In this experiment, soil moisture was significantly depleted in the severe deficit treatment.
- In a comprehensive economic analysis, other sources of differences between full irrigation and deficit irrigation need to be considered. Some of these sources are related to the cost of harvesting, weed control, and re-planting.
- Salt management—may not be flushing/leaching salts out of the root zone over the multiple irrigation seasons.

CONCLUSIONS

In California, it is important to develop improved strategies to maximize water productivity under variable water supplies. Alfalfa appears to be highly conducive to deficit irrigation strategies during low water years due to its deep rooted characteristics, flexibility, high yields under partial irrigation, and drought tolerance compared with many crops. Strategies may encompass multiple objectives of farm profitability, risk avoidance, and water quality protection through more efficient irrigation system such as SDI and irrigation management as the major driver of water use efficiency. Deficit irrigation of alfalfa under SDI may be a viable strategy for coping with recurrent water shortages happening in California. In this one-year study in one treatment, yields were about 80% of normal when applied irrigation water was cut to ½ of full ET requirements. This strategy may increase alfalfa WUE under SDI to a value of 0.33 ton ac^{-1} in^{-1} as a result of greater water application efficiency, higher distribution uniformity over time and space, and yield production utilizing the more productive early growth periods. Overall, the mid-summer deficit irrigation strategy can keep the relatively high hay yields of the first part of growing season when alfalfa WUE is higher and reduce water applications during the summer when yield is lower and hay quality is poorer. Further work is needed to better understand the impacts of deficit irrigation on alfalfa yields and on plant stands over long-term period, as well as on forage quality, influence of varieties, and economic aspects related to production.

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